First Results for Electron Neutrino Appearance in MINOS

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Outline

- Brief intro to neutrino oscillation
- MINOS beam and detectors
- The ν_e appearance analysis:
  - selection of candidate ν_e events
  - background analysis with near detector data
  - far detector prediction
  - results
- Summary

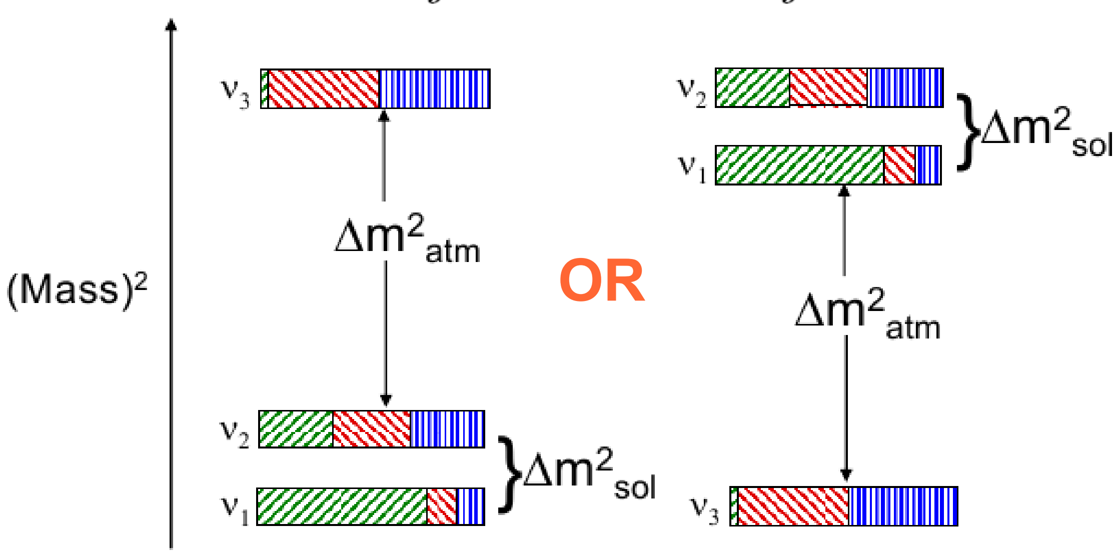
Neutrino Oscillation

$$S_{jk} = \sin\theta_{jk}$$
$$C_{jk} = \cos\theta_{jk}$$

$$U_{MNSP} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & C_{23} & S_{23} \\ 0 & -S_{23} & C_{23} \end{pmatrix} \begin{pmatrix} C_{13} & 0 & S_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -S_{13}e^{i\delta} & 0 & C_{13} \end{pmatrix} \begin{pmatrix} C_{12} & S_{12} & 0 \\ -S_{12} & C_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

atmospheric **δ and θ_{13} are unknown** **solar**

$$\Delta m^2_{ij} = m^2_i - m^2_j$$



Mass hierarchy is unknown

Best limit by CHOOZ reactor neutrino experiment: $\sin^2 2\theta_{13} < 0.15$

For the remainder of this talk, "signal" plots and numbers assume:

$\Delta m^2_{31} \sim \Delta m^2_{32} > 0$

$\sin^2 2\theta_{13} = 0.15$

$\delta = 0$

Measuring θ_{13}

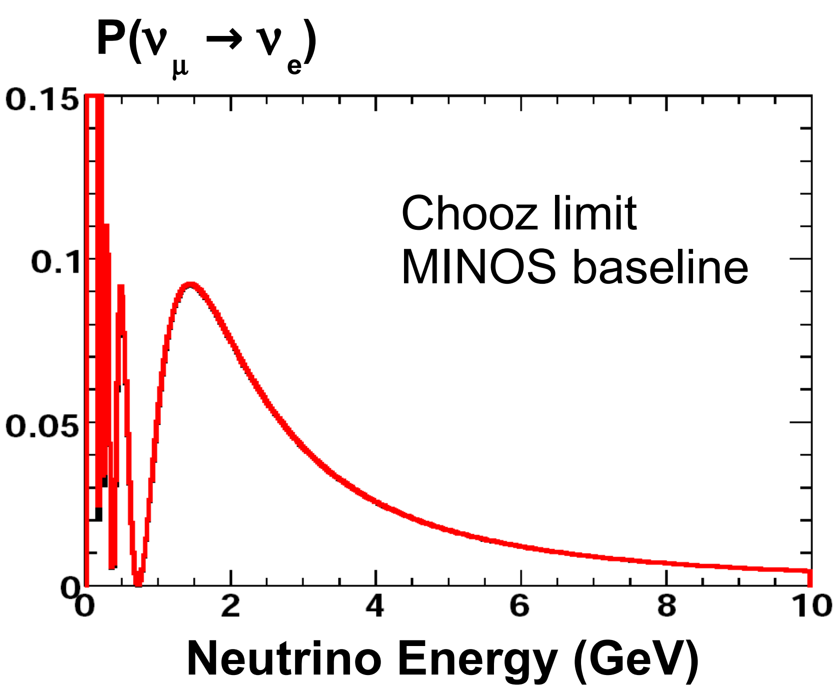
$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2}$$

ν_e appearance probability

$$+ 2\alpha \sin\theta_{13} \cos\delta \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \cos\Delta$$

$$- 2\alpha \sin\theta_{13} \sin\delta \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \sin\Delta$$

$$+ \alpha^2 \sin^2 2\theta_{12} \cos^2 \theta_{23} \frac{\sin^2 A\Delta}{A^2}$$



Matter effect:

$$A \equiv \frac{G_f n_e L}{\sqrt{2}\Delta} \approx \frac{E}{11 \text{ GeV}}$$

$$\Delta \equiv \frac{\Delta m^2_{31} L}{4E}$$

$$\alpha \equiv \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$$

θ_{13} is coupled with δ and the mass hierarchy

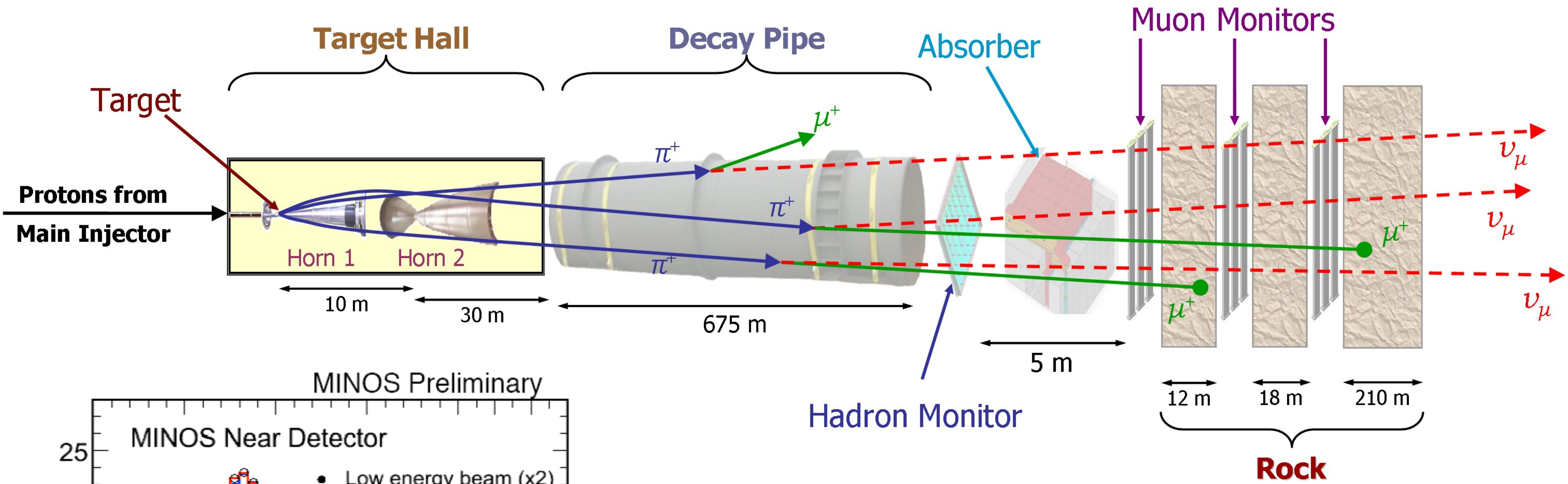
MINOS (Main Injector Neutrino Oscillation Search)

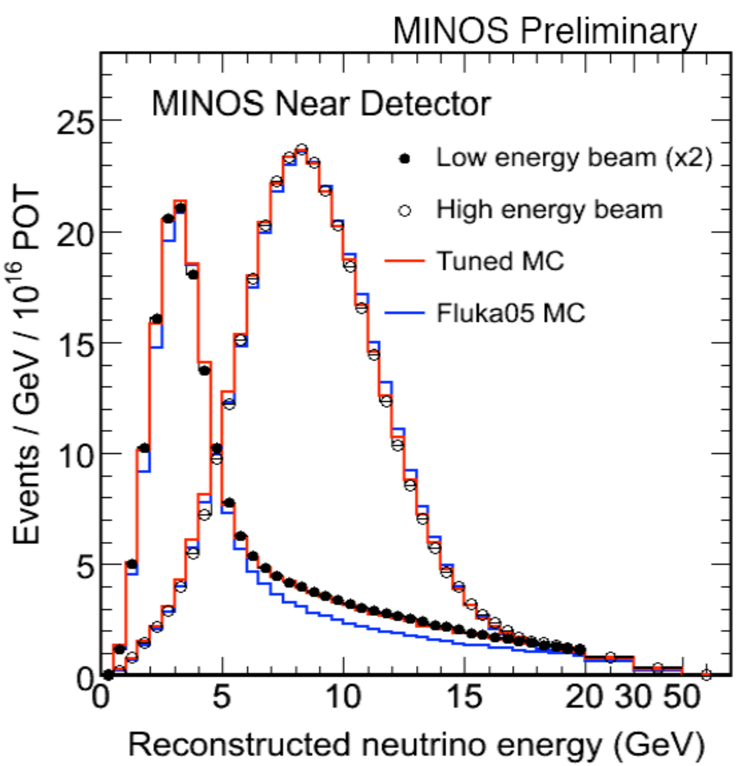
Produce a beam of muon neutrinos at Fermilab

Use data from a near detector to form a prediction for the far detector (number of events and/ or energy spectrum)

Neutrino oscillation will cause a deviation from the prediction in the far detector

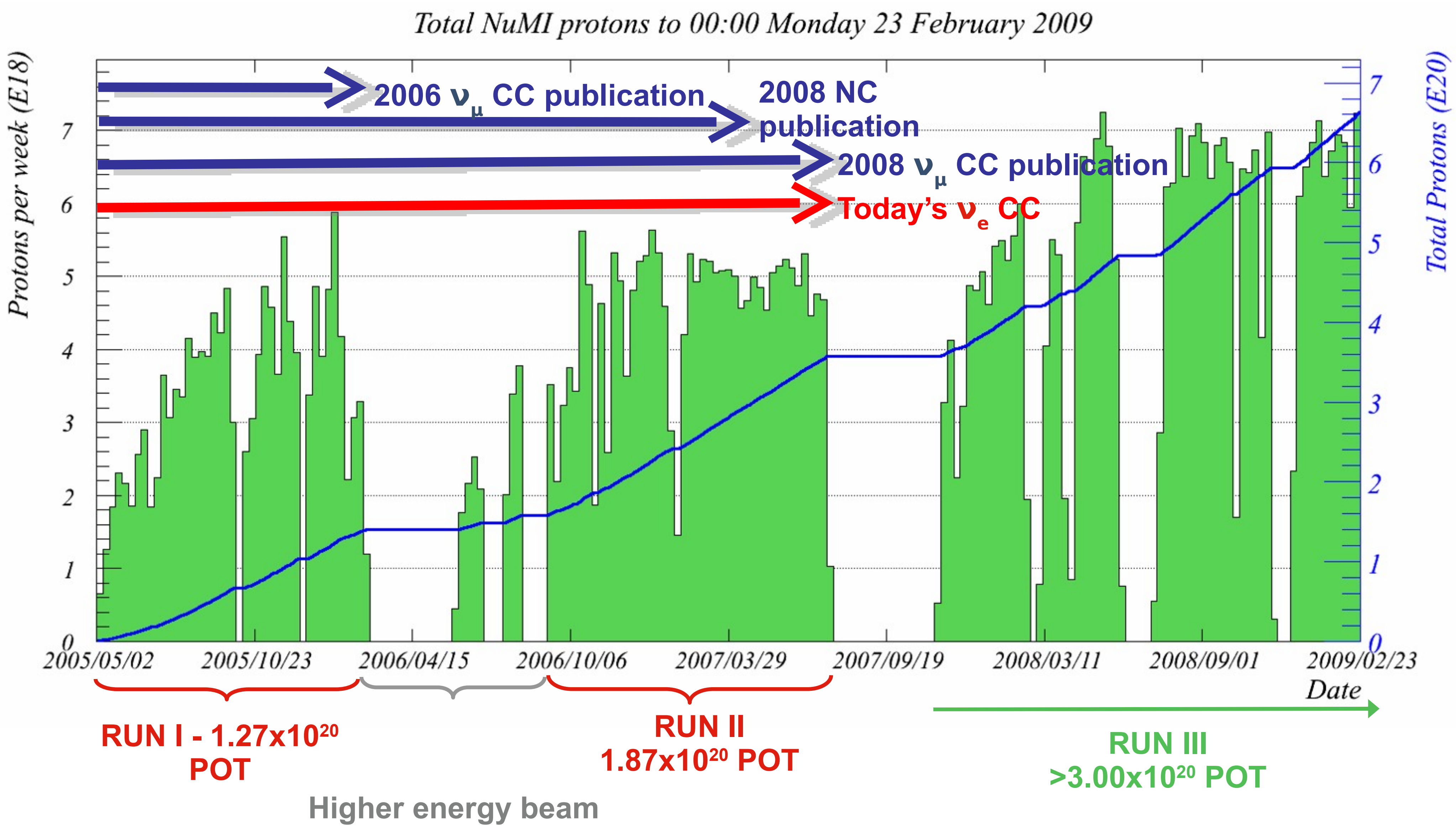
NuMI Beam



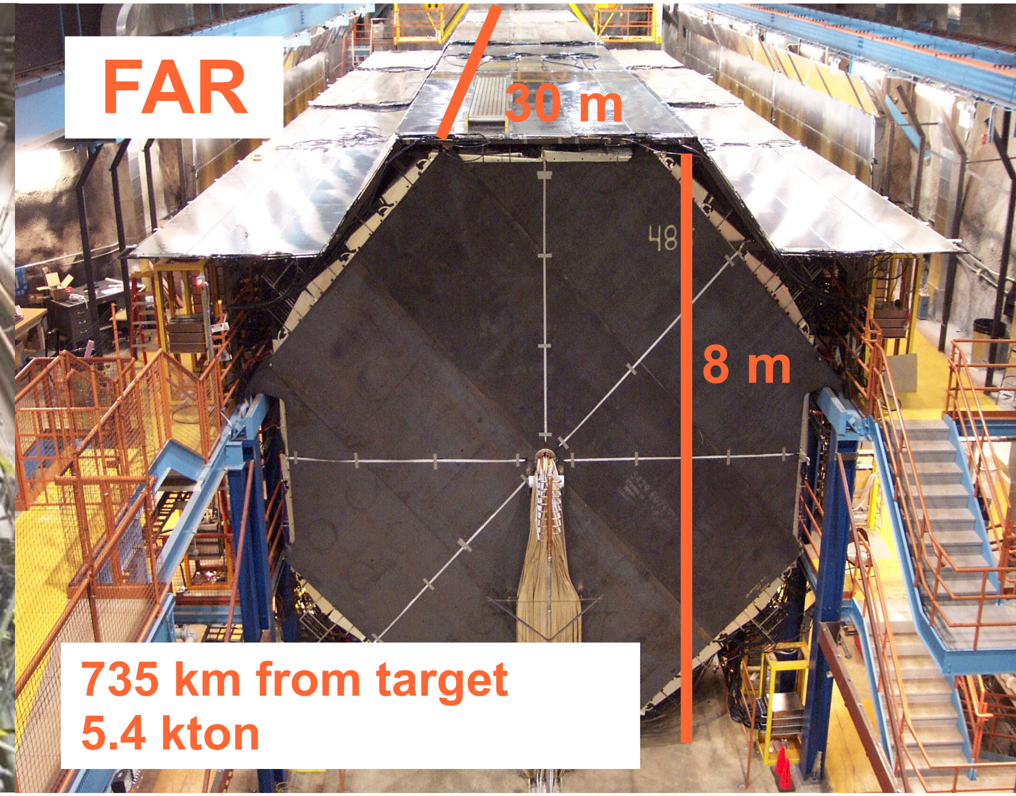


- 120 GeV protons from the Main Injector
- carbon target
- magnetic horns focus secondary particles
- particles decay to neutrinos
- target position affects energy spectrum
- timing structure: 10μs spill every 2.2 s
- currently, 3e13 protons per spill
- Beam is mostly ν_μ with a small (~1.3%) ν_e component which we know to 10%

NuMI Beam: Protons-on-Target

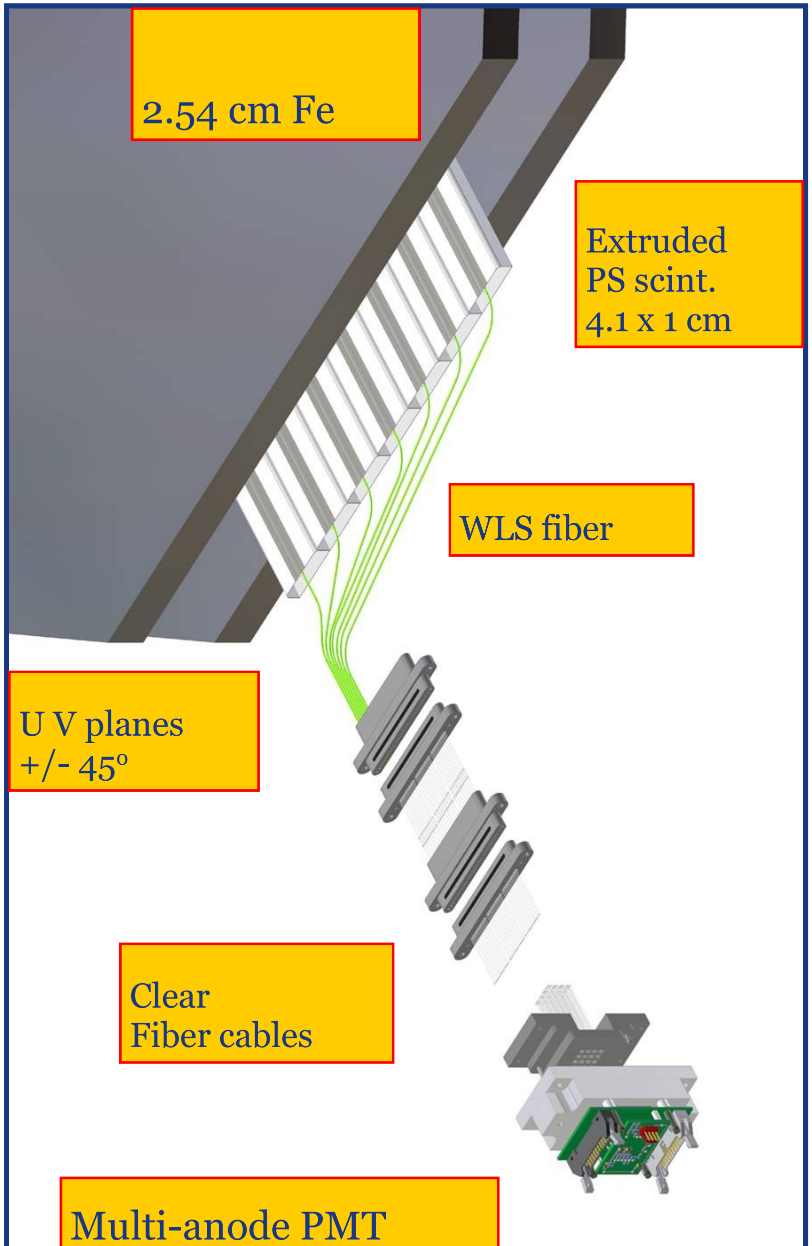


MINOS detectors



alternating layers of steel plates and scintillator strips
in a 1.3 T toroidal magnetic field

MINOS detectors

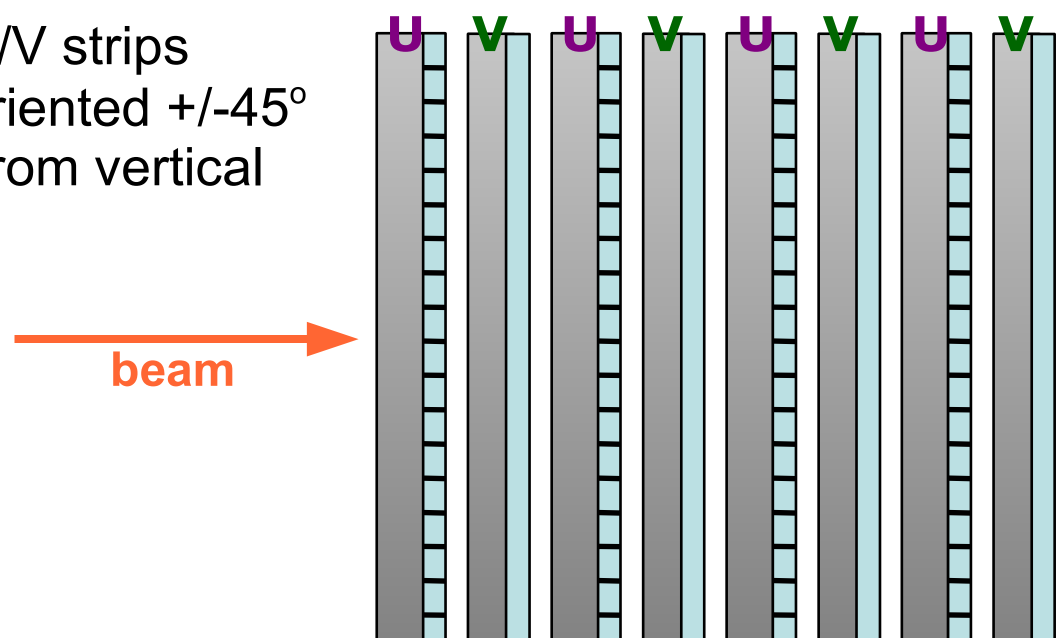


steel thickness: 2.54cm ~1.44X_0
strip width: 4.12cm (Moliere rad ~3.7cm)

Strips in adjacent planes are oriented orthogonally enabling 3D reconstruction

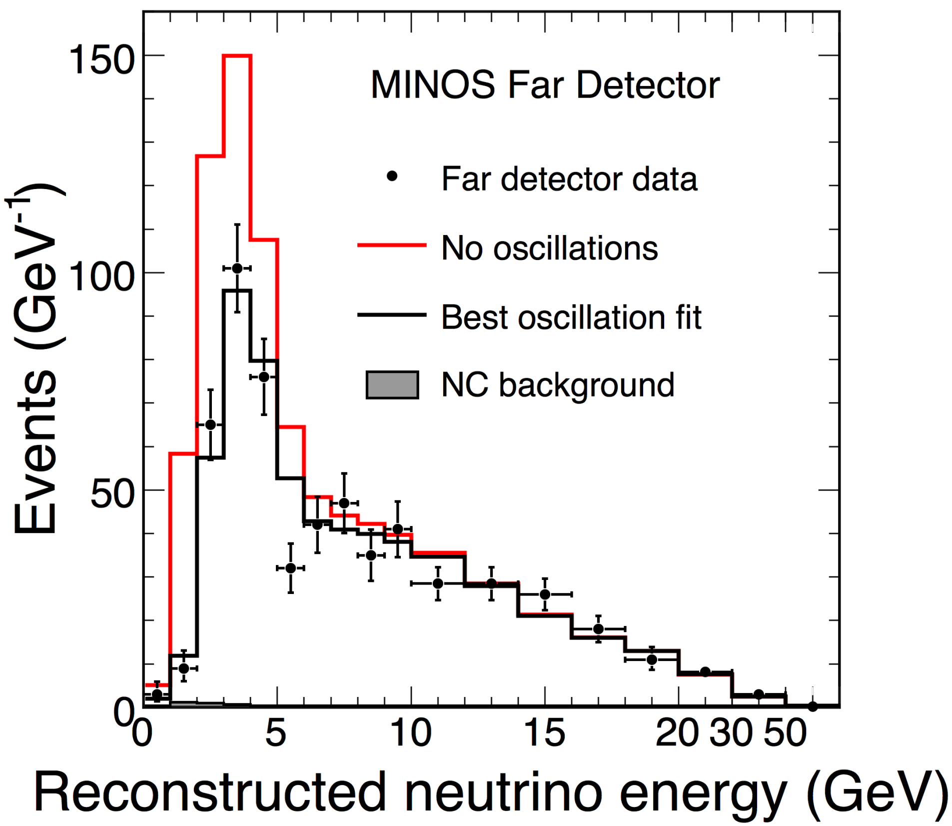
Strips have WLS fibers read out by multi-anode PMTs

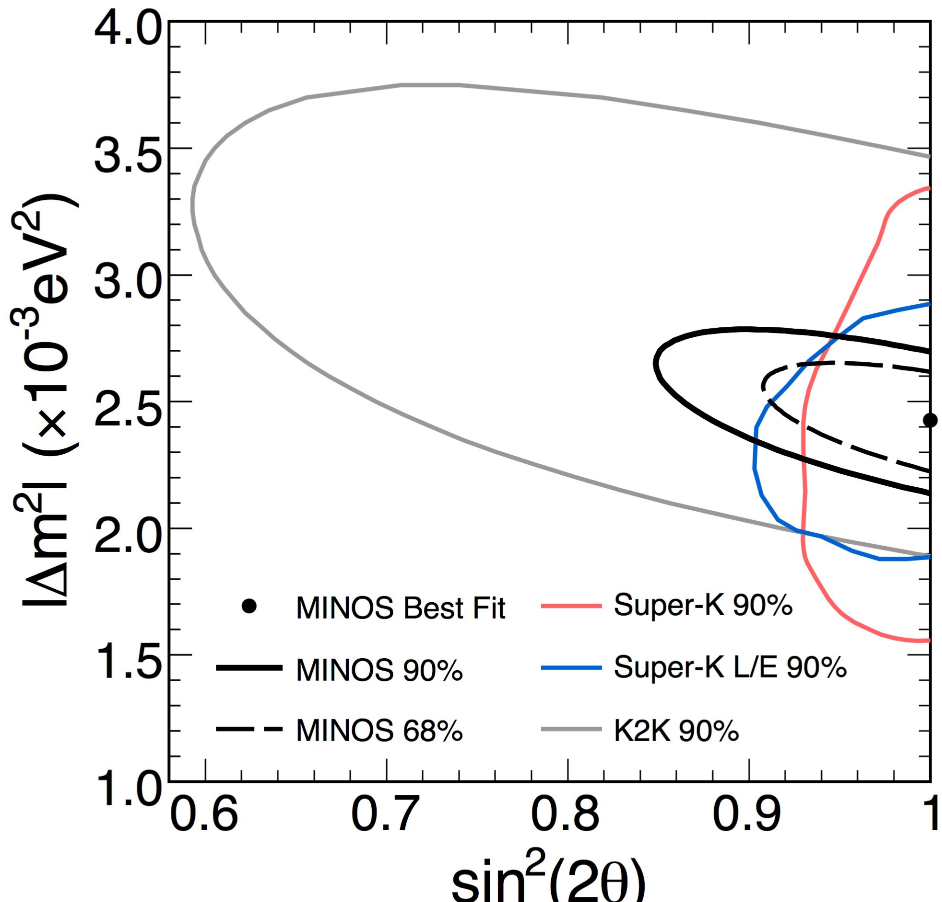
U/V strips oriented +/-45° from vertical



MINOS ν_μ Disappearance

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta)\sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$





$|\Delta m^2_{32}| = (2.43 \pm 0.13)\times 10^{-3}$ eV^2 (68% CL)

$\sin^2 2\theta_{23} > 0.9$ (90%CL)

Most precise measurement of $|\Delta m^2_{32}|$ yet

Searching for ν_e appearance

Determine the selection criteria for ν_e candidate events.

Use near detector data (where we expect no oscillated ν_e's) to study the background.

Extrapolate the near detector background sample to get the far detector background prediction.

Blind Analysis:
Sideband study - Examine far detector data outside of the signal region to test the analysis.

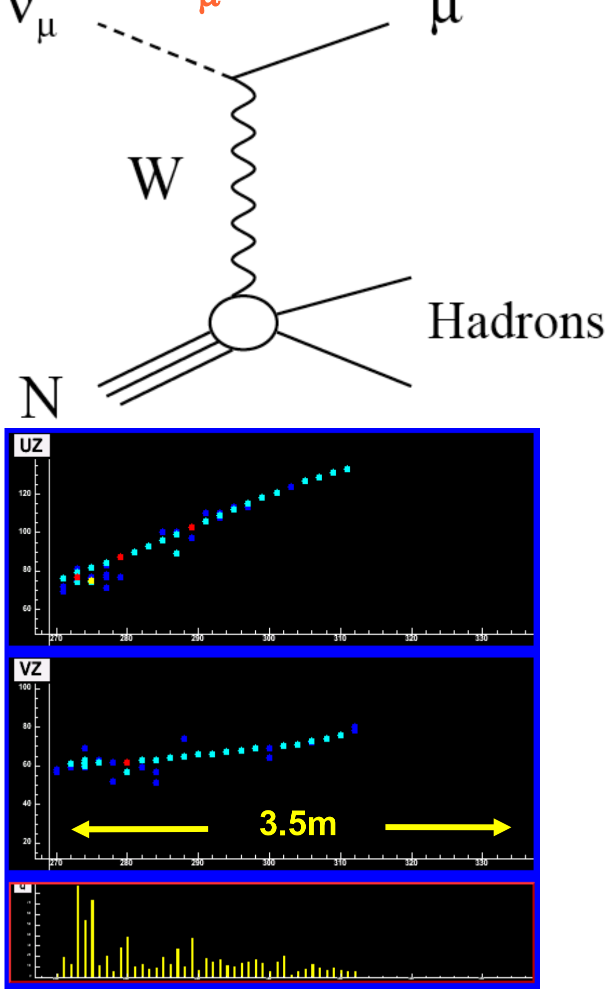
Open the box – Examine far detector data in the signal region and look for an excess of ν_e-like events over predicted background in far detector.

At the CHOOZ limit, we would expect an excess of only 6-12 events! (3.14e20 POT)

Neutrino Events at MINOS

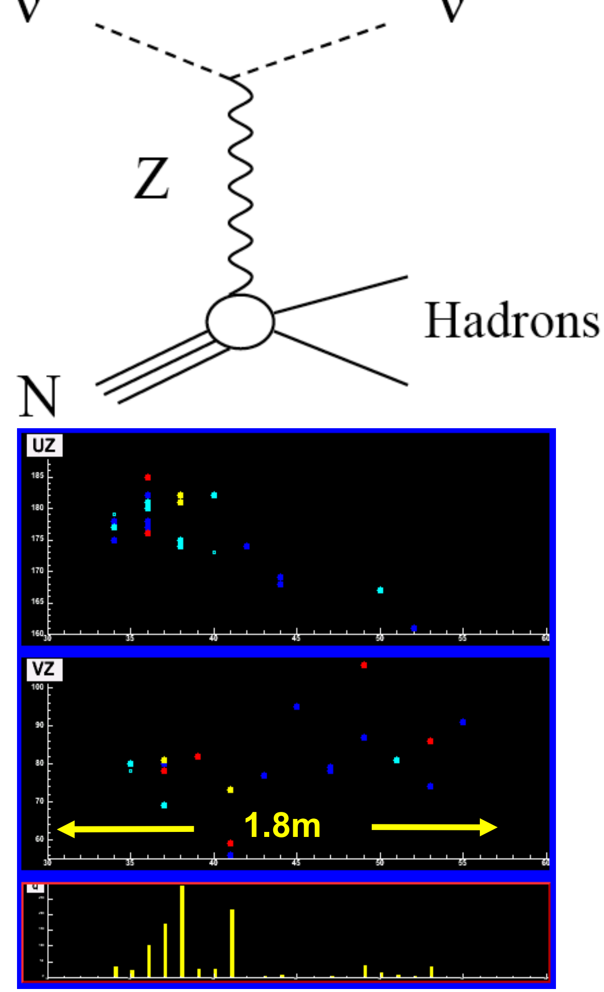
(MC event displays)

ν_μCC



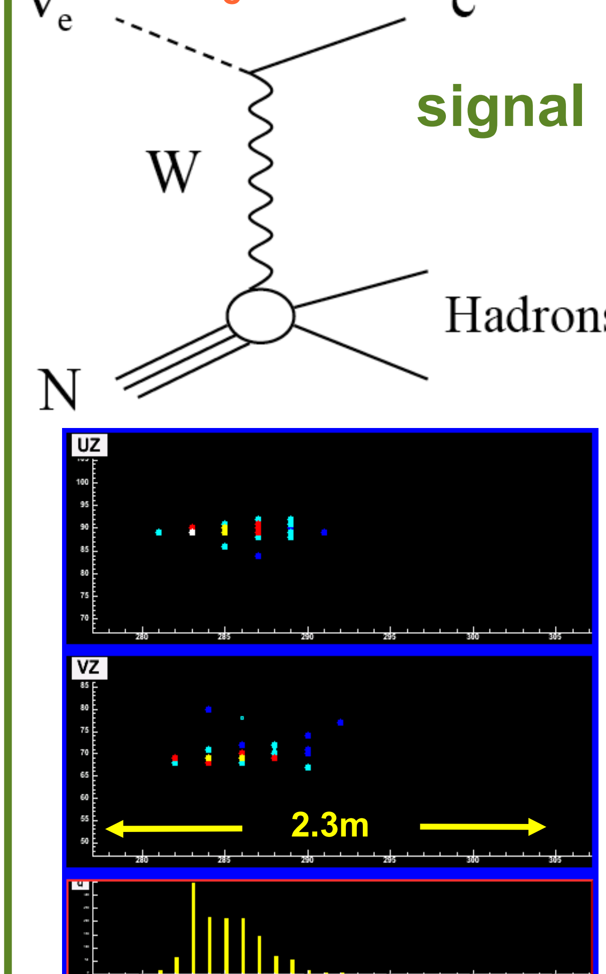
long μ track+ hadronic activity at vertex

NC



short event, often diffuse

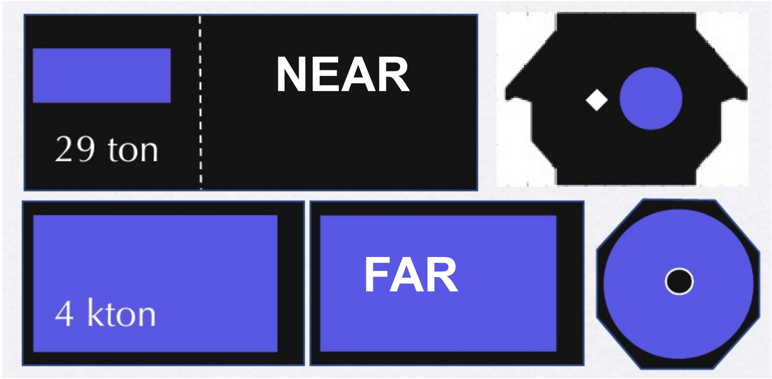
ν_eCC



signal

short, with typical EM shower profile

Event Selection



Select good beam-induced events:

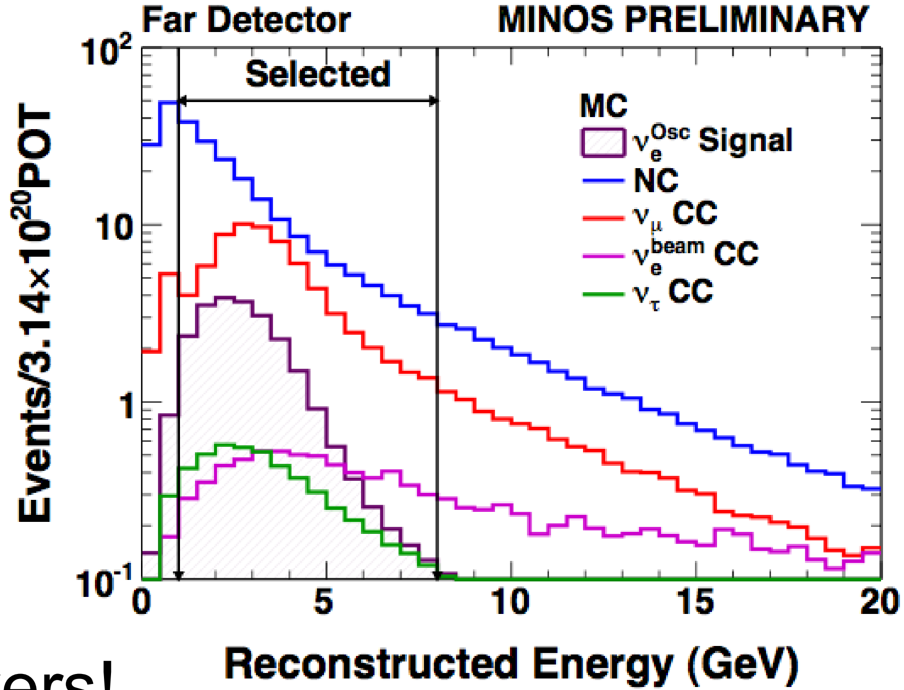
- Detector quality and beam quality
- Fiducial volume
- Reject cosmic tracks

(selects 1188 far detector data events)

Preselection: reduce background

- reject events with a long track
- at least 1 shower
- at least 4 hit planes in a row
- reco energy 1-8 GeV
- improves signal:background from 1:55 to 1:12

(selects 227 far detector data events)

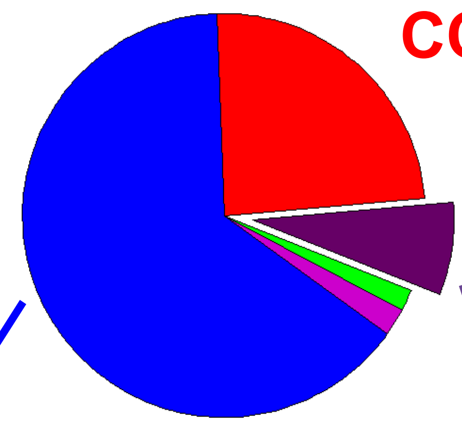


ν_e selector: select the ν_e-like showers!

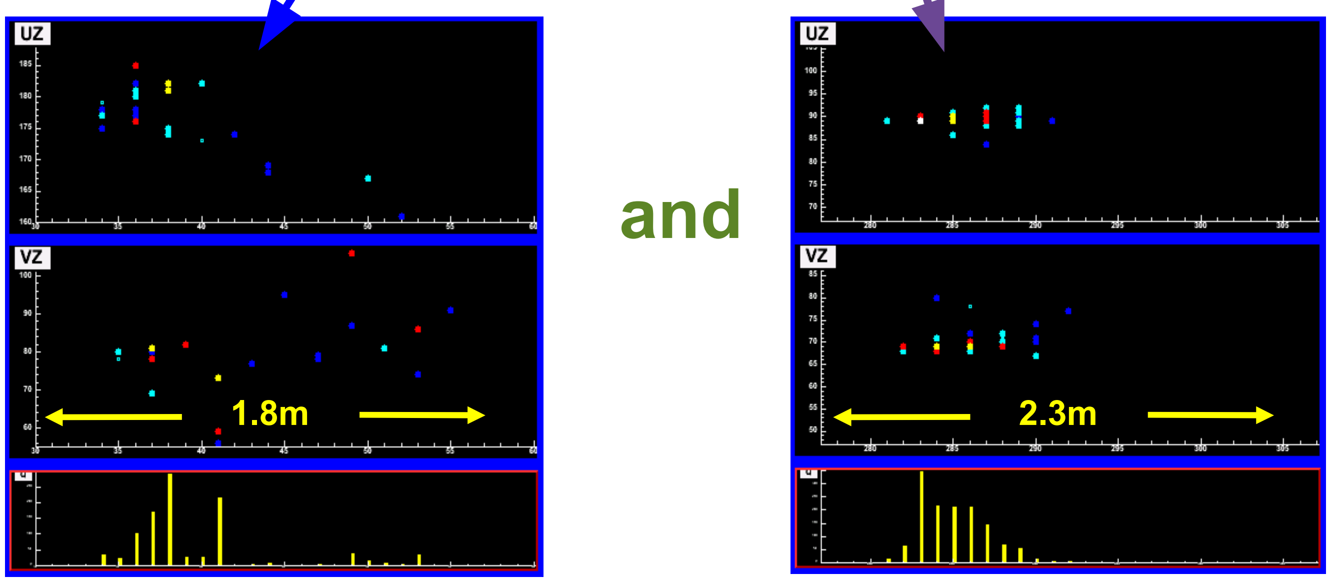
Selecting ν_e-like showers

After preselection, the background is mostly NC

Far detector breakdown after preselection:



Need a method to discriminate

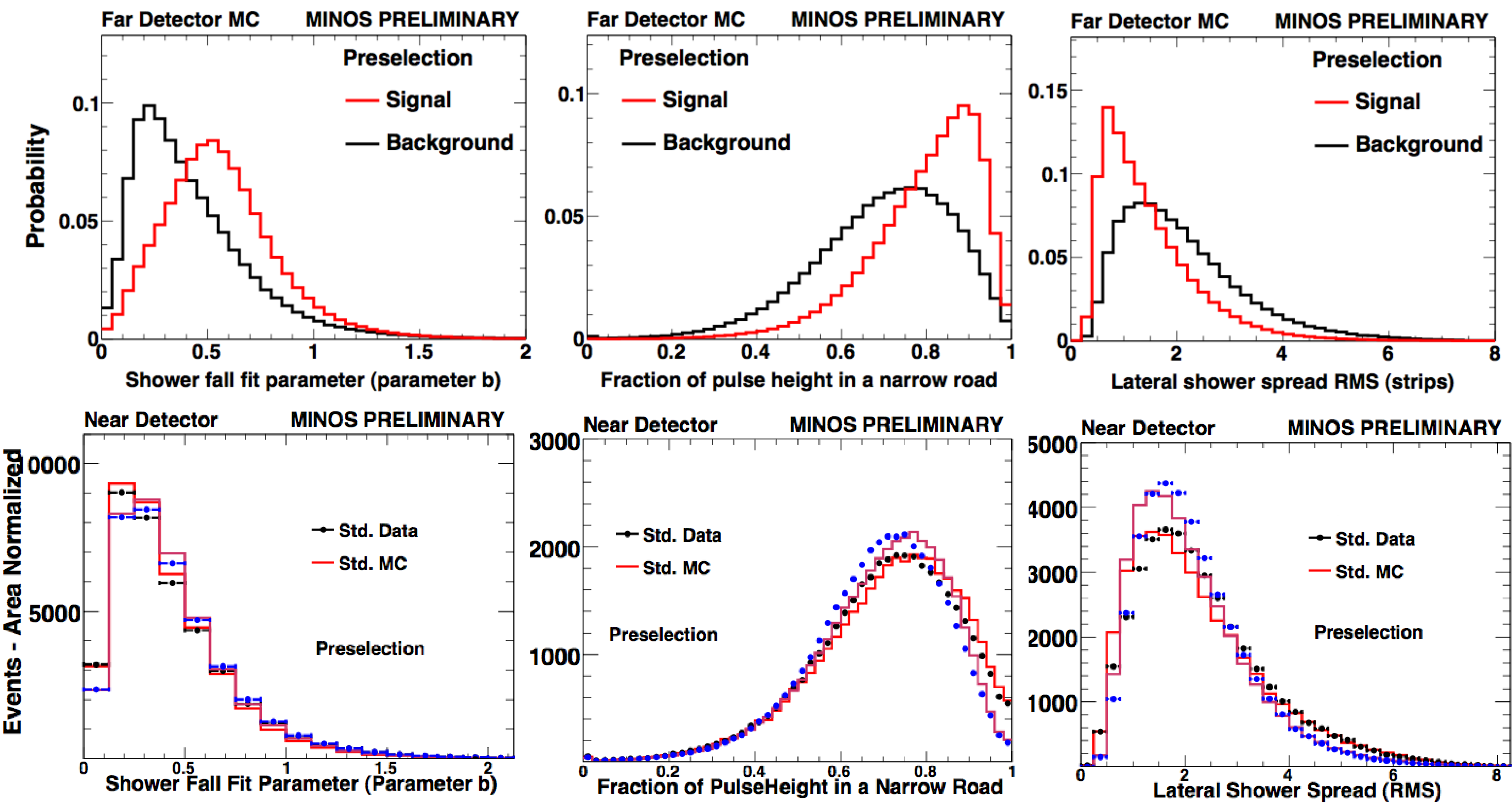


(background) (signal)

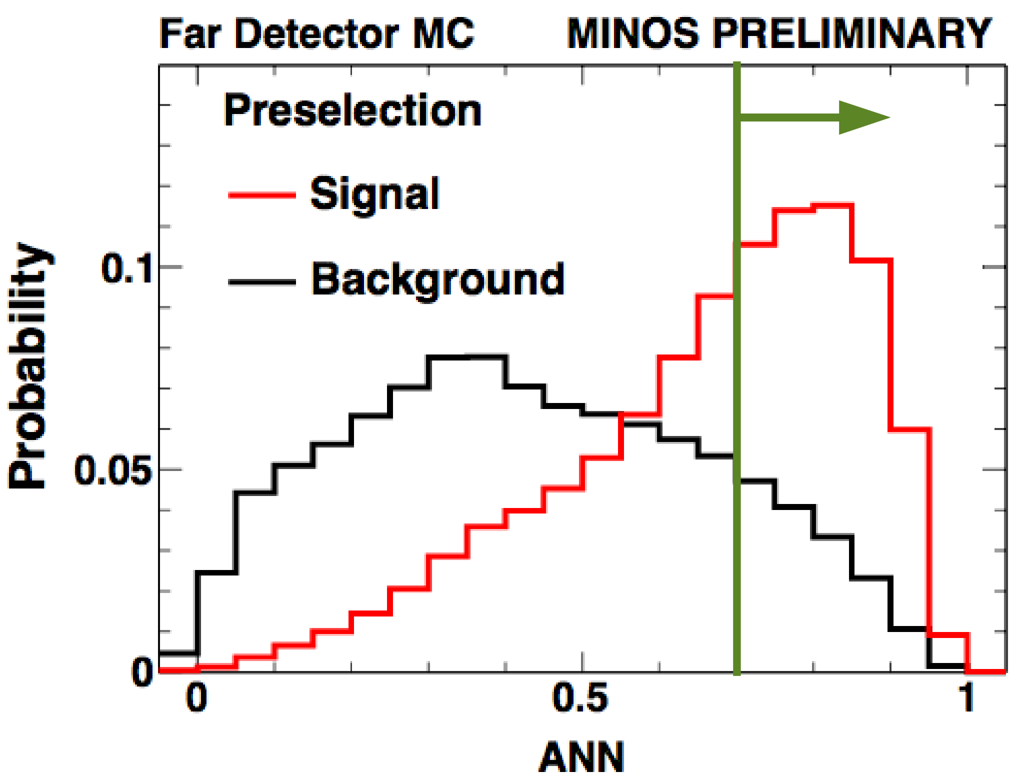
Artificial Neural Net (ANN)

11 input variables that characterize the shower shape

some of the best variables....



Artificial Neural Net (ANN)



With a cut of ANN>0.7:
signal efficiency 41%
NC rejection >92.3%
CC rejection >99.4%
signal/background 1:4

this is our primary ν_e selection method

Library Event Matching (LEM)

ν_e selection by hit pattern recognition

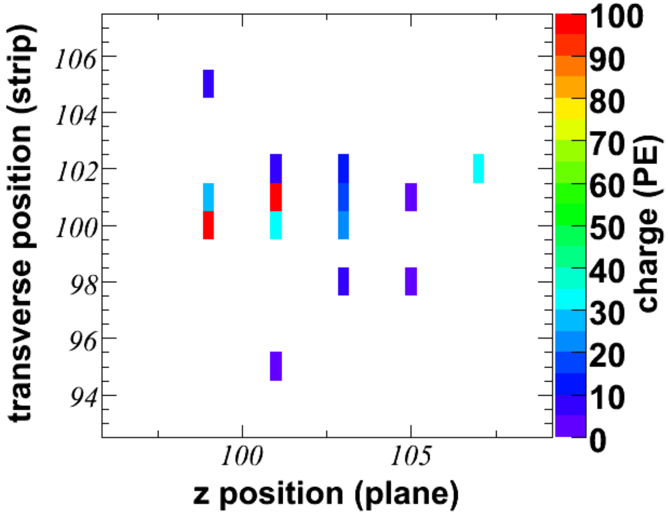
an alternative to ANN

Create a library of CC ν_e and NC events

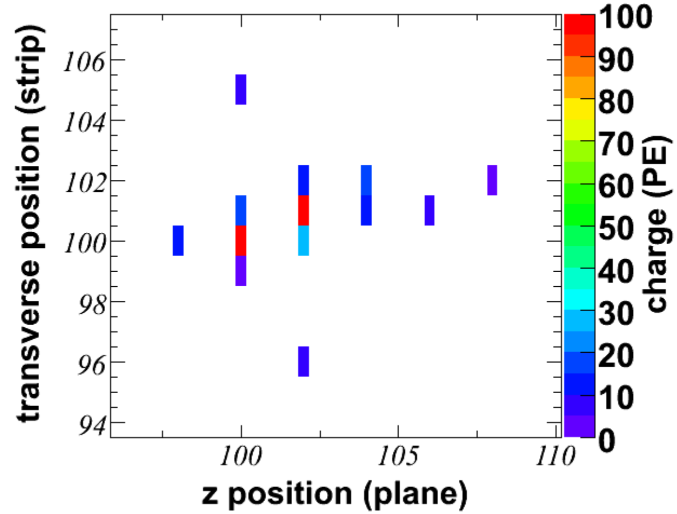
For each input event, select the 50 best matches from the library and construct a likelihood based on:

- the fraction of 50 best matches that are CC ν_e
- mean y of the CC ν_e best matches (y = fraction of energy given to hadrons)
- mean fraction of charge in shared strips of the CC ν_e best matches

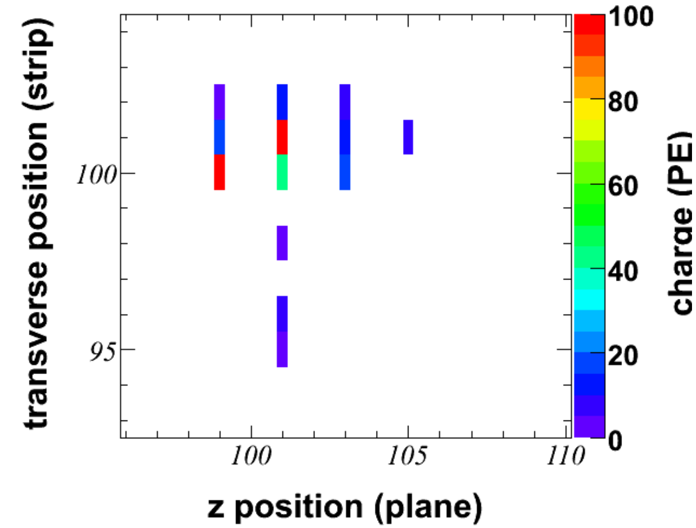
input data event



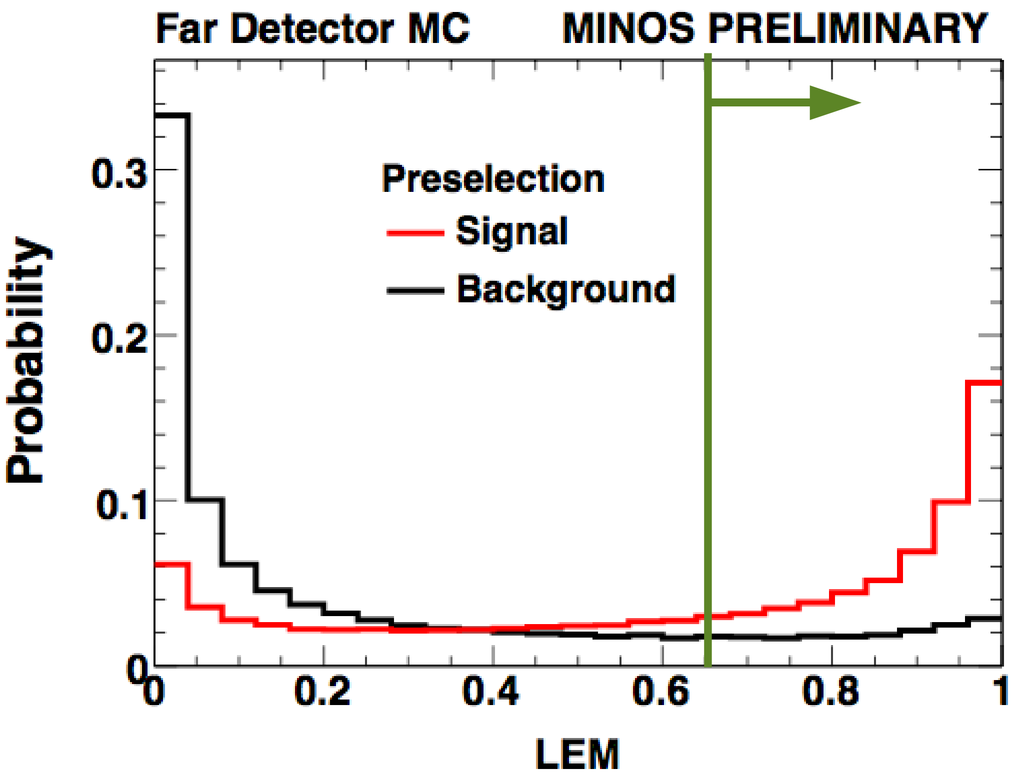
good match



bad match



Library Event Matching (LEM)



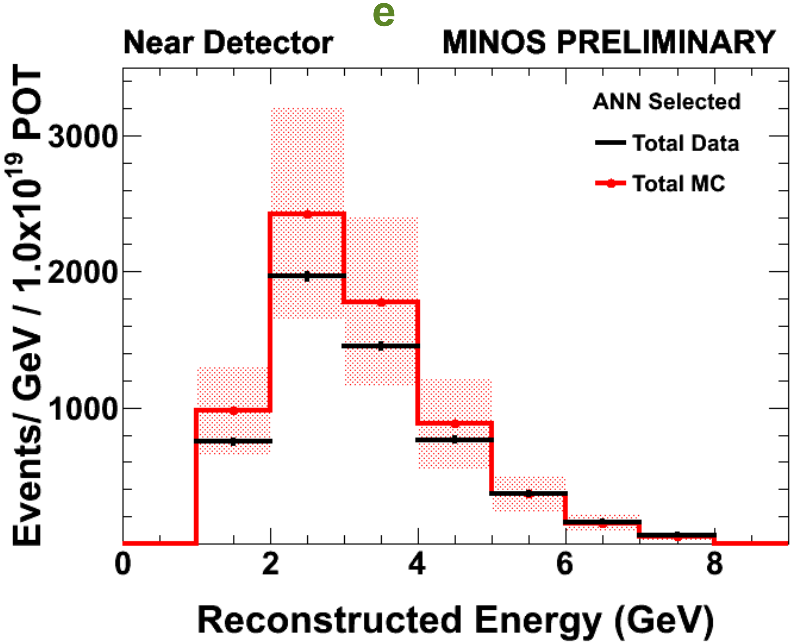
With a cut of LEM>0.65:
signal efficiency 46%
NC rejection >92.9%
CC rejection >99.3%
signal/background 1:3

this is our secondary ν_e selection method

ND data to FD prediction?

Now that we have the ν_e selection criteria, how do we make the far detector prediction?

ANN-selected near detector ν_e candidates



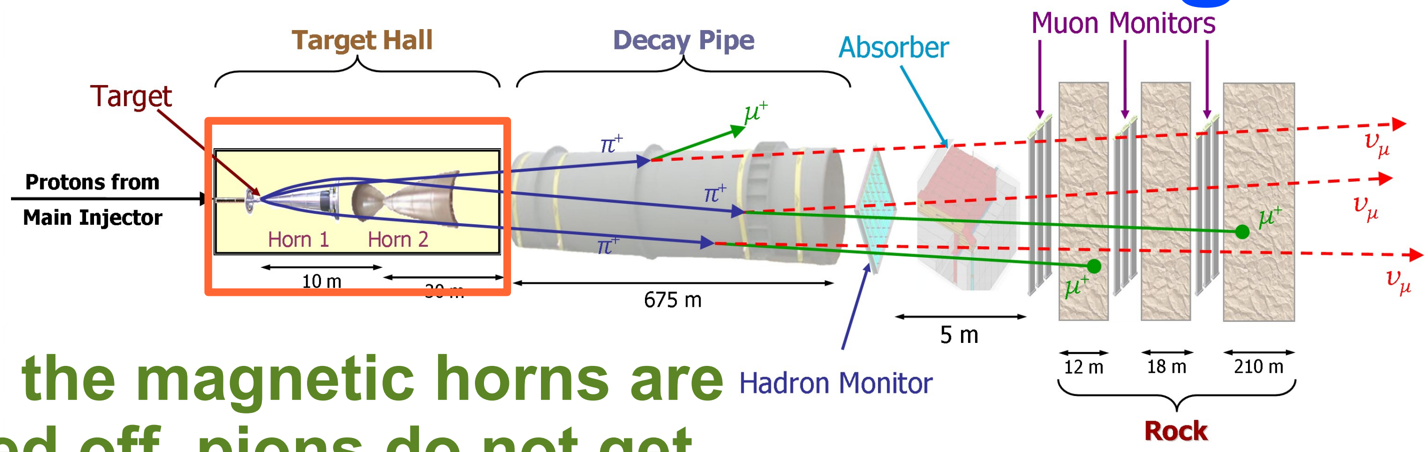
To first order, need only account for differences in flux (~1/R^2) and fiducial volume.

For more accurate extrapolation, need to consider oscillation (ν_μ disappearance affects CC component), detector effects, etc.

Need to separate the near detector data into CC ν_μ, NC, beam ν_e components.

We can use horn-off data to do this...

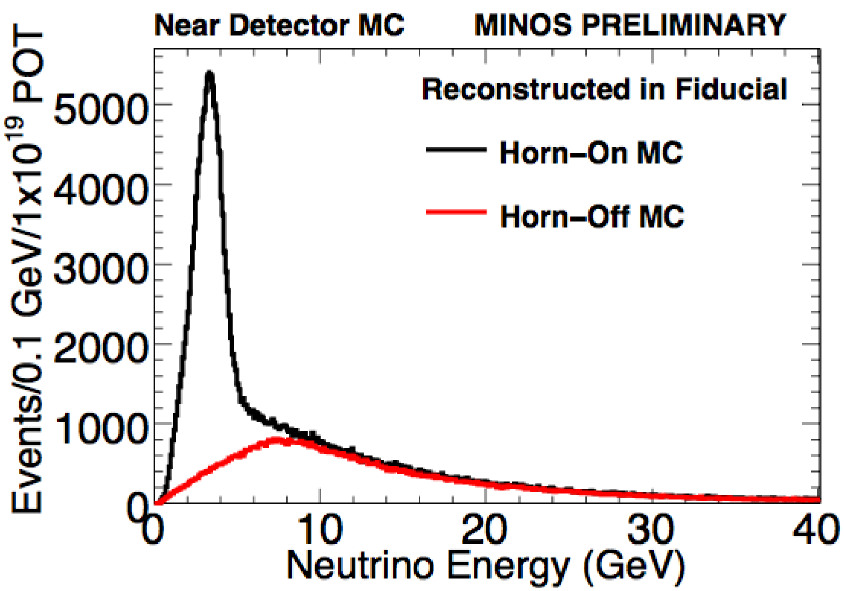
Horn-Off Beam Configuration

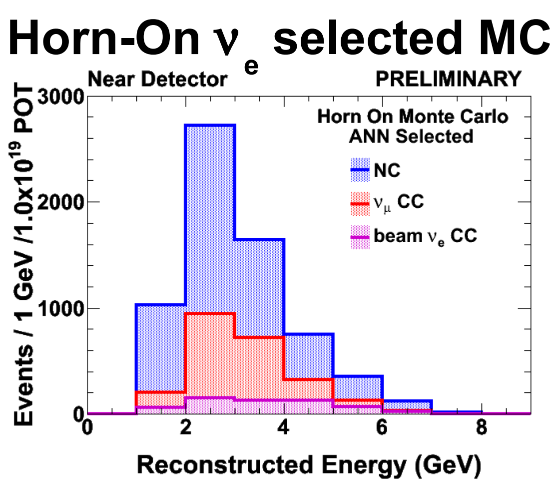


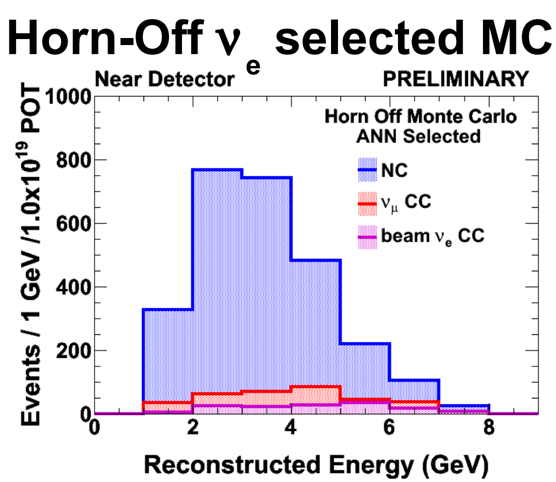
5.5e18 POT of data in this configuration

When the magnetic horns are turned off, pions do not get focused, and the low energy peak of the neutrino energy spectrum disappears.

There is less contamination from low energy (short track) CC ν_μ events in the ν_e selected near detector data.







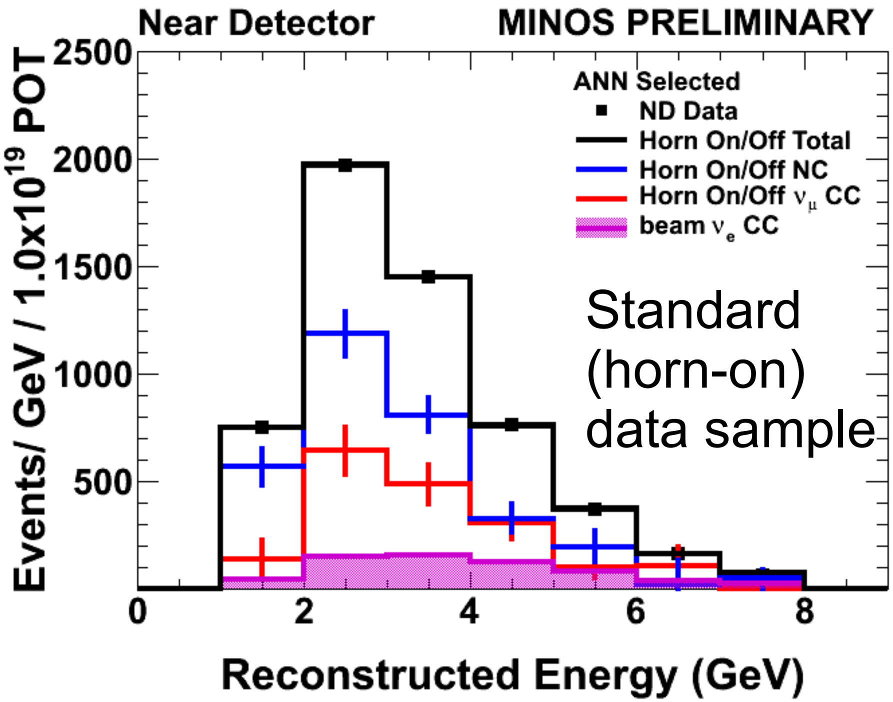
Data-Driven Background Separation: Horn-On/Horn-Off

How does horn-off data help us?

The horn-off to horn-on ratio of selected CC and NC events is well-modeled in the MC

$r_{NC} = N_{NC}^{OFF}/N_{NC}^{ON}$

$r_{CC} = N_{CC}^{OFF}/N_{CC}^{ON}$



We have two data samples with different (and unknown) CC and NC components. But we do know (from the MC) the *relative* number of CC and NC events between the two samples.
→ we can calculate the invidivual components using the ratios

(The beam ν_e component is taken from MC)

Muon Removal Technique

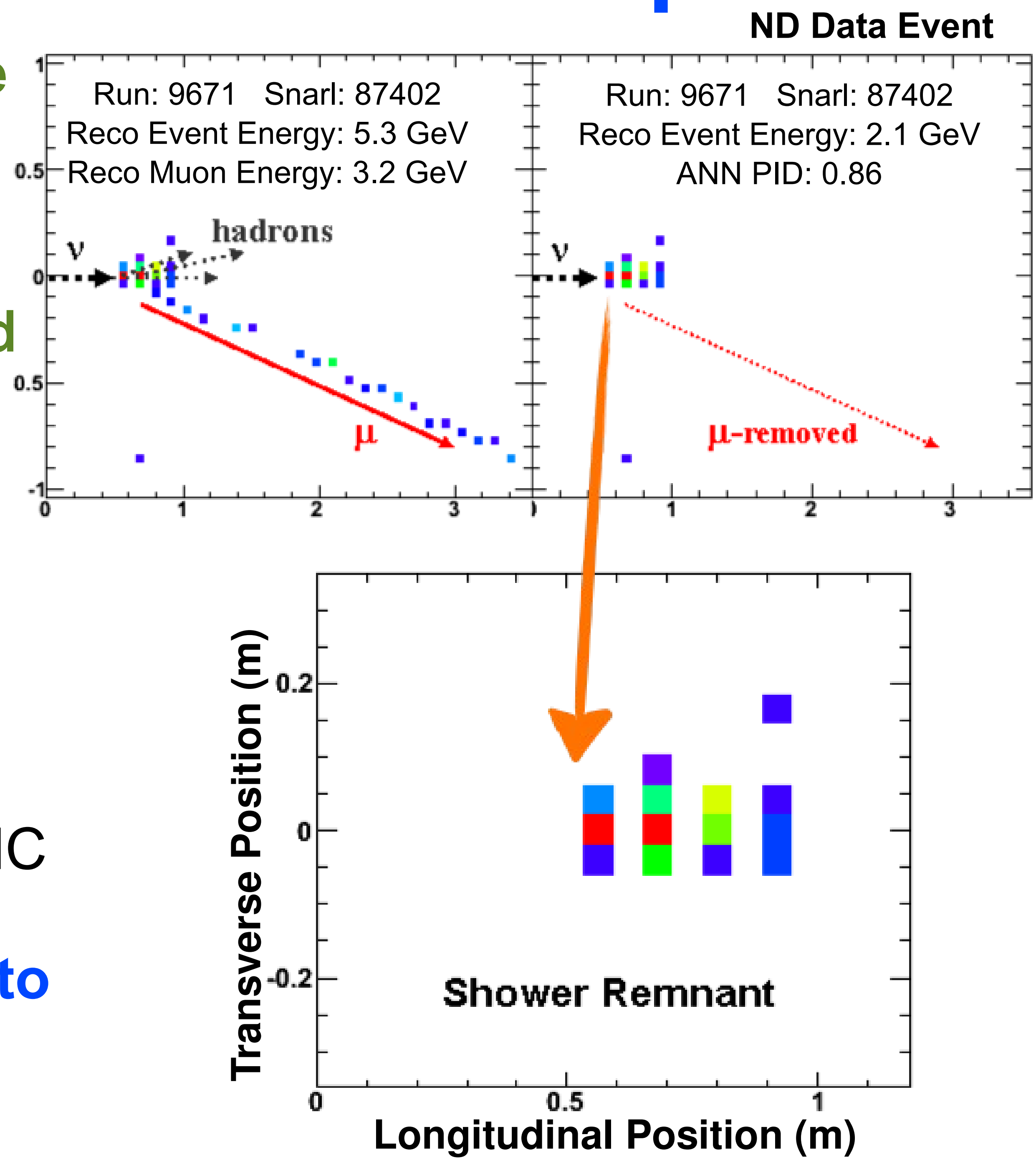
As a cross-check for the Horn on/off background analysis...

Muon Removed Charged Current (MRCC)

1) take good CC events
2) remove the hits associated with the muon
3) re-reconstruct the hadronic shower

can do this for data and MC

an independent sample to study hadronic showers



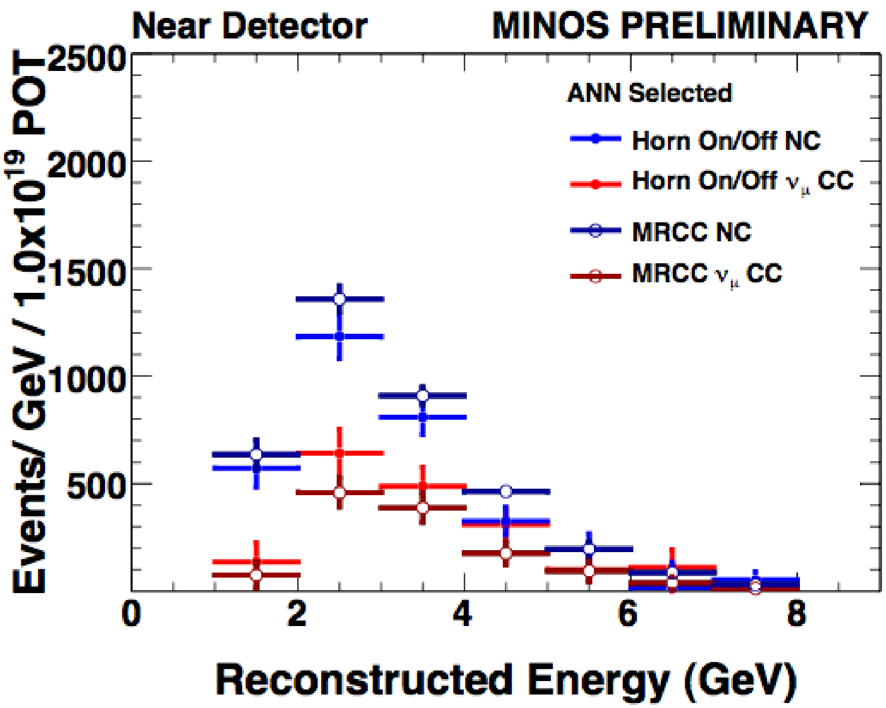
MRCC

As a cross-check for the Horn on/off background analysis...

Apply ν_e selection to the MRCC data and MRCC MC and use data/MC ratio to predict NC component of standard data selection

$$NC_i^{corr} = \frac{MRCC_i^{data}}{MRCC_i^{MC}} \times NC_i^{MC}$$

Results are consistent with Horn on/off method



Extrapolation to Far Detector

Far/Near Ratio:

Ratio of MC ν_e selected events in bins of reco energy

far detector background prediction

$$F_i^{predicted,\alpha} = N_i^{\alpha} \times \left(\frac{f_i^{\alpha}}{n_i^{\alpha}} \right)$$

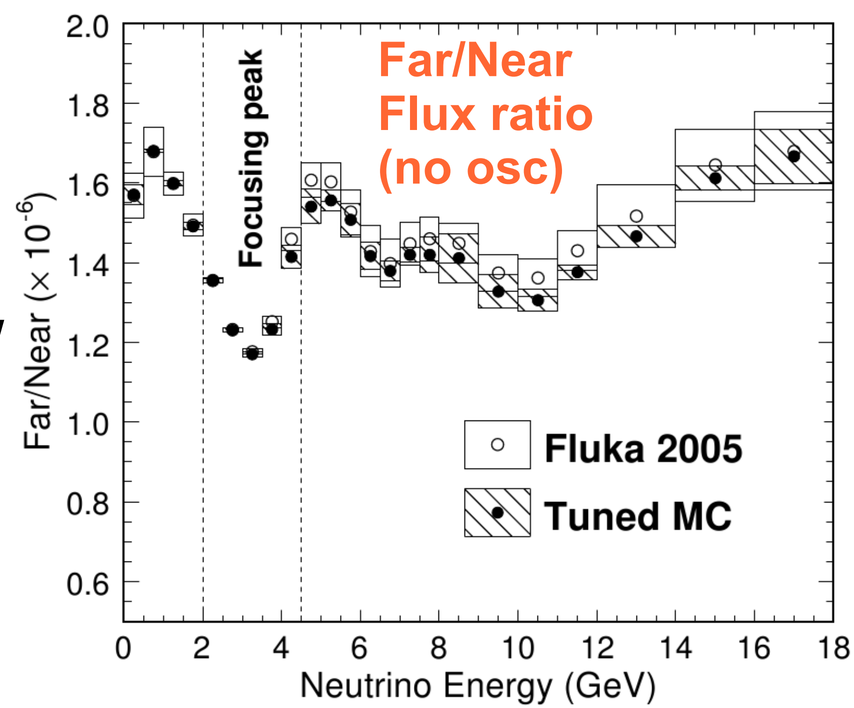
near detector selected data

Far/Near ratio

Far/Near ratio accounts for:

Largest effects

- Flux ($1/R^2$, geometry, focusing, acceptance, decay kinematics)
- Fiducial volume (4000 tons/ 29 tons)
- energy smearing
- ν_μ disappearance
- detector effects (next slide)
- etc



Far/Near Differences

Far/Near differences that are taken into account by ratio:

- difference in fiber length (light level difference)

- multiplexing in the far detector (8 fibers per PMT channel)

- one-sided readout in the near detector

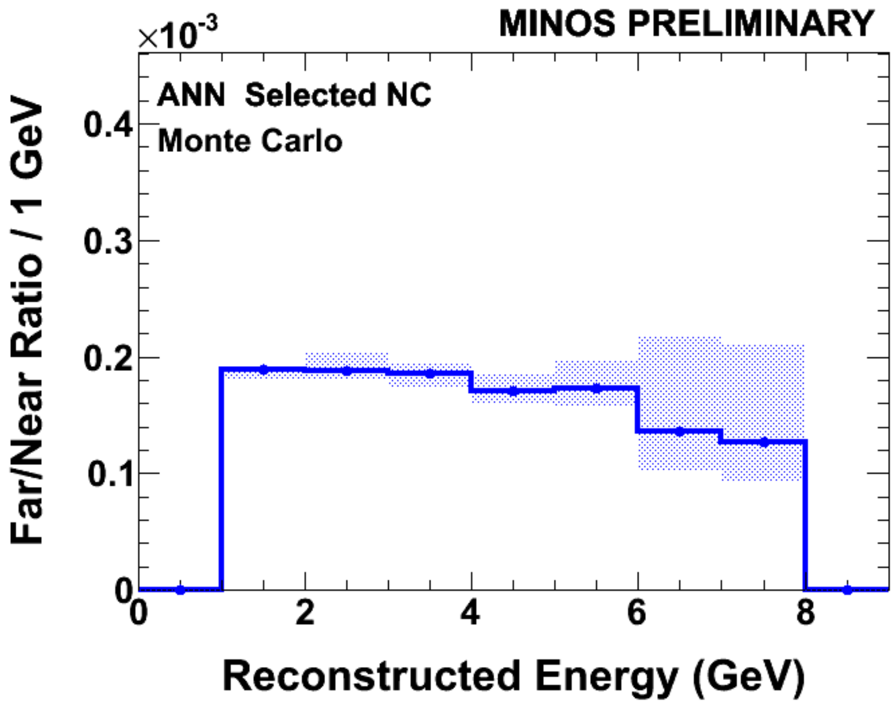
- PMTs (64-channel in near, 16-channel in far) - different crosstalk pattern, gains, front end electronics

- faster readout in near detector

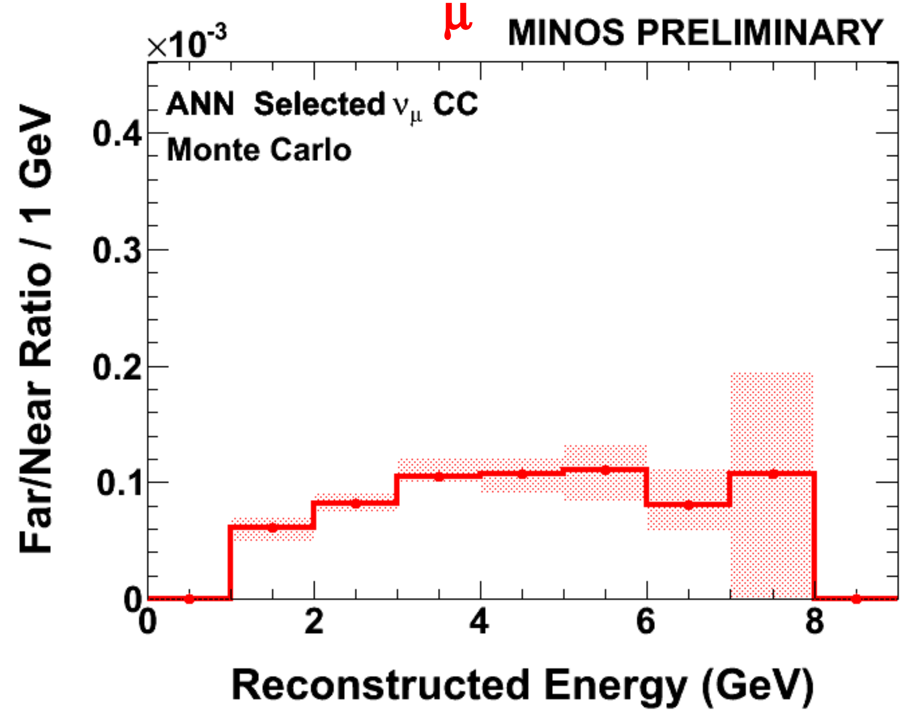
- relative energy calibration

Far/Near Ratio

NC



CC ν_μ



Far detector beam ν_e prediction is taken from MC.

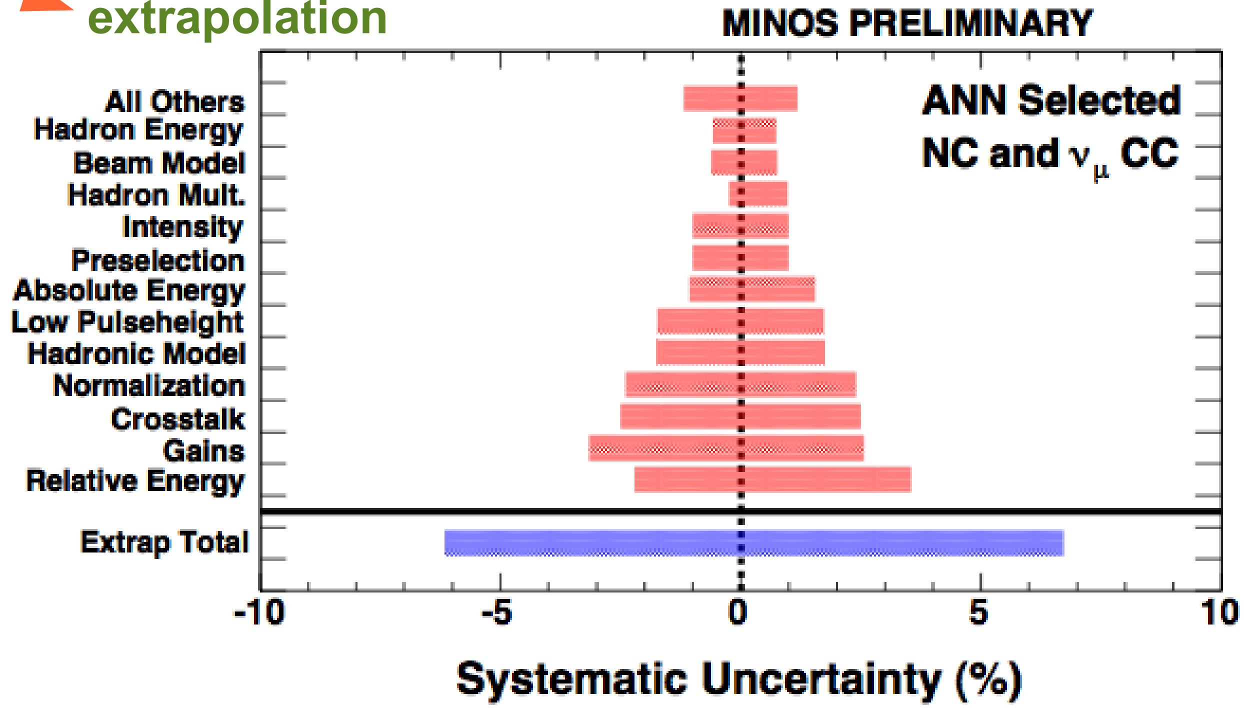
Predictions for oscillated CC ν_τ and CC ν_e (signal) are made based on the CC ν_μ spectrum at the near detector.

Systematic Uncertainties in Far Detector Background Prediction

Extrapolation:
6.4%
Horn-On/Horn-Off Method:
3.5%

Total Systematic Uncertainty:
7.3%

Uncertainties related to extrapolation



Far Detector Background Prediction

Far Detector Background Prediction for 3.14e20 POT:

27 ± 5(stat) ± 2(syst)

26.6 events: 18.2 NC, 5.1 CC ν_μ, 1.1 CC ν_τ, 2.2 beam ν_e

Sidebands

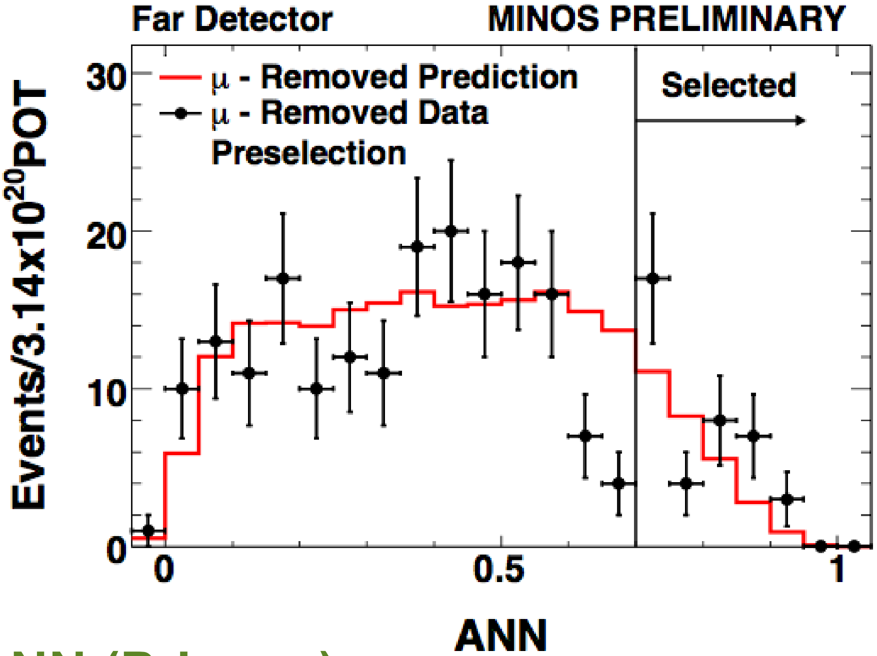
Before opening the box in the signal region, we examined three far detector data samples with no expected signal:

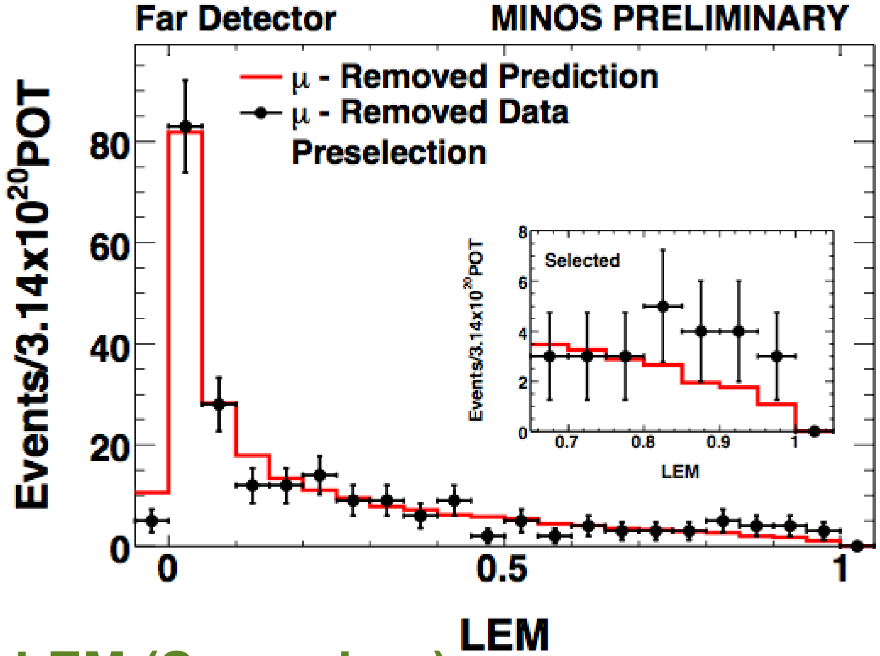
- far detector muon removed events

- far detector muon removed w/electron events

- far detector preselected events that fail the ν_e selection cut

Muon Removed Far Detector Events



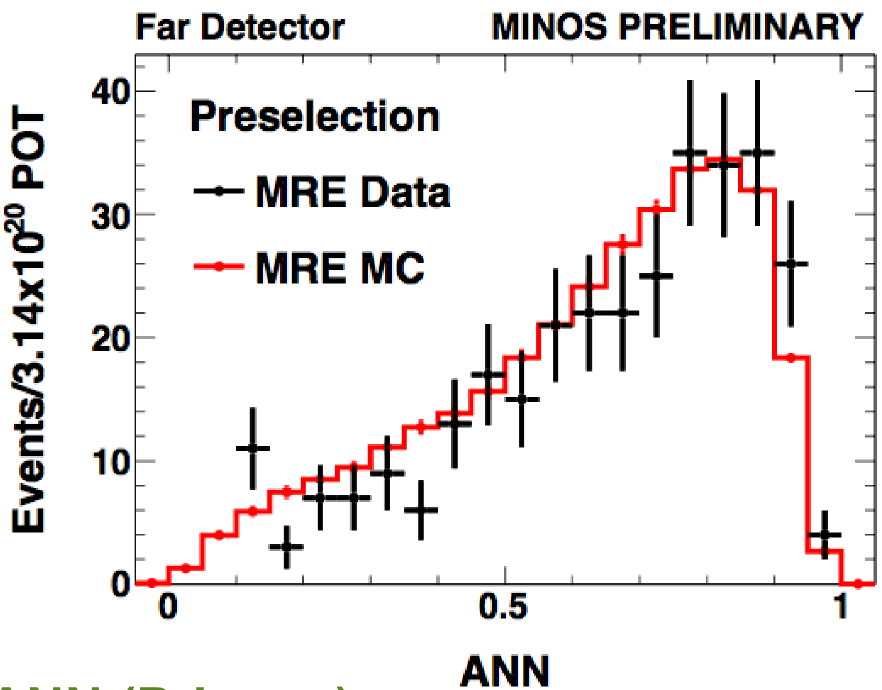


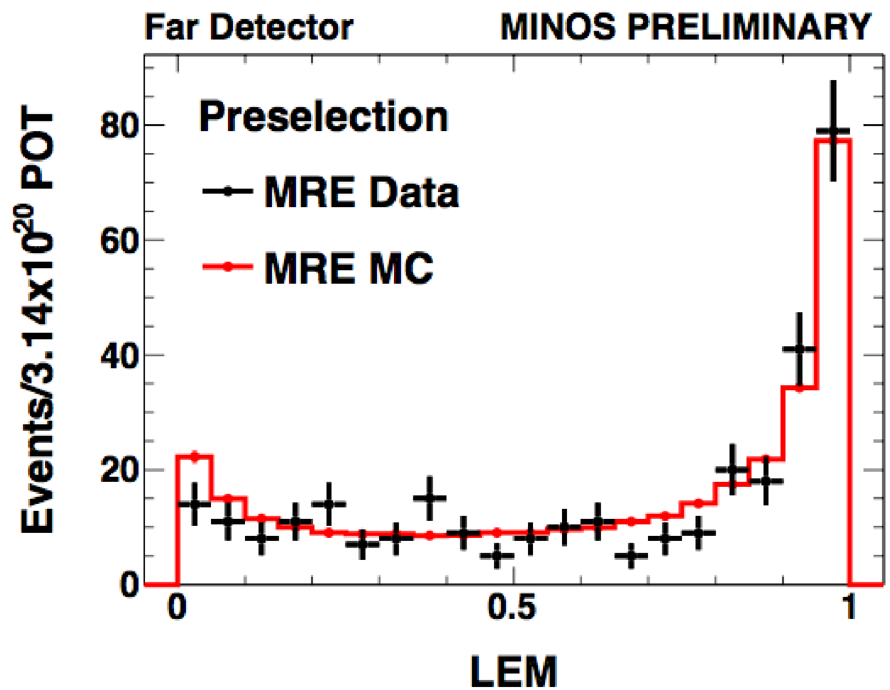
ANN (Primary):
observe 39 events
expect 29 ± 5(stat) ± 2(syst)

LEM (Secondary):
observe 25 events
expect 17 ± 4(stat) ± 2(syst)

- Muon removed events were originally ν_{μ} CC events, so there is no signal in this sample.
- Good cross check that ANN/LEM behave as expected for hadronic showers (the major background)

Muon Removed + Electron Far Detector Events





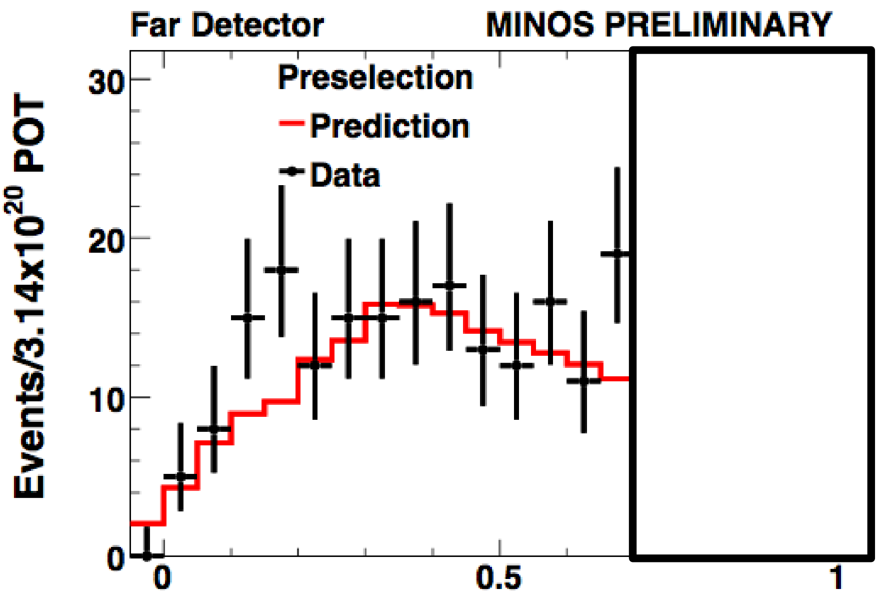
ANN (Primary):
observe 159 events
expect 152 ± 13(stat) ± 12(syst)

LEM (Secondary):
observe 180 events
expect 176 ± 13(stat) ± 17(syst)

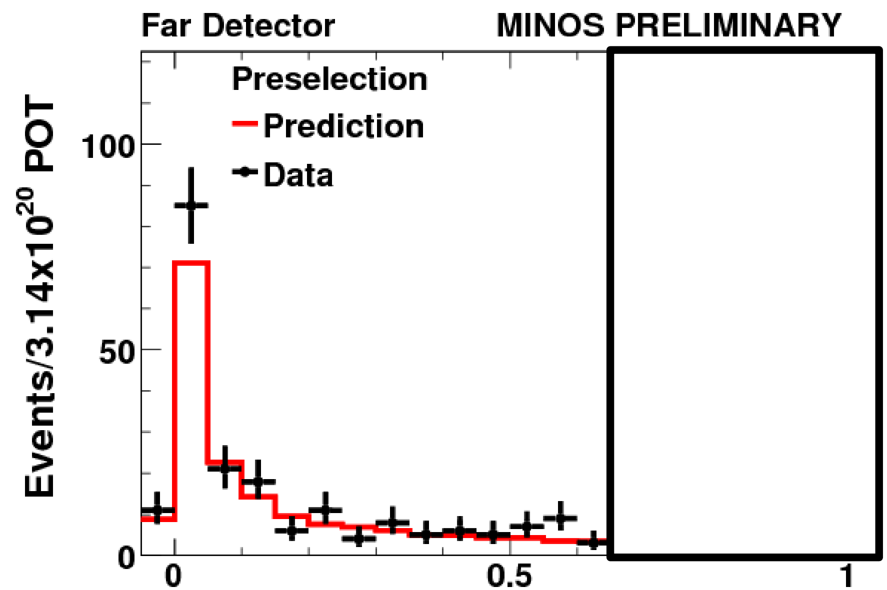
- Take muon removed events, add an electron and re-reconstruct
- Allows us to simulate signal with a real hadronic shower
- Good cross check that ANN/LEM behave as expected for signal-like events.

Events Outside Signal Cut

ANN<0.7



LEM<0.65



ANN (Primary):
0<ANN<0.55
observe 146 events
expect 132 ± 12(stat) ± 8(syst)

0.55<ANN<0.7
observe 46 events
expect 38 ± 6(stat) ± 2(syst)

LEM (Secondary):
0<LEM<0.55
observe 176 events
expect 157 ± 13(stat) ± 3(syst)

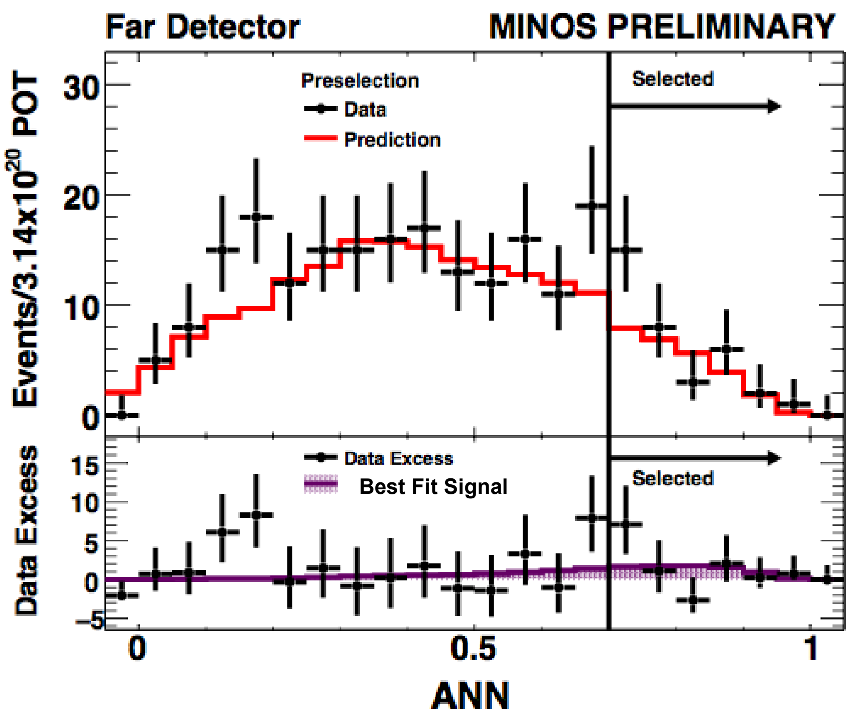
0.55<LEM<0.65
observe 12 events
expect 7 ± 3(stat) ± 0(syst)

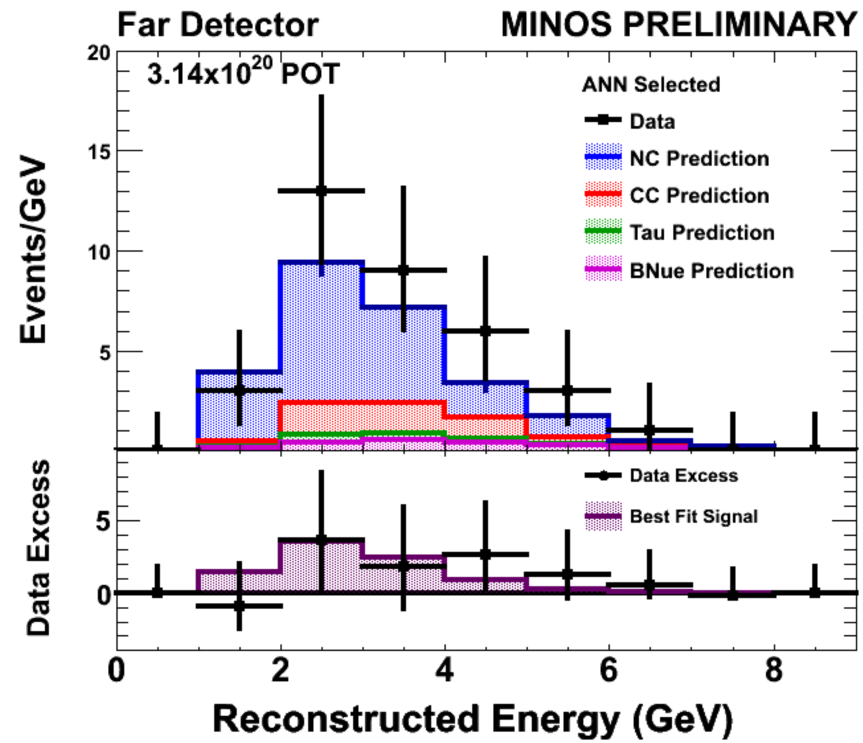
- Good test of entire analysis chain - background prediction and extrapolation to far detector.

ν_e Appearance Results for 3.14e20 POT

ν_e Selected Far Data

ANN (Primary Selection Method)



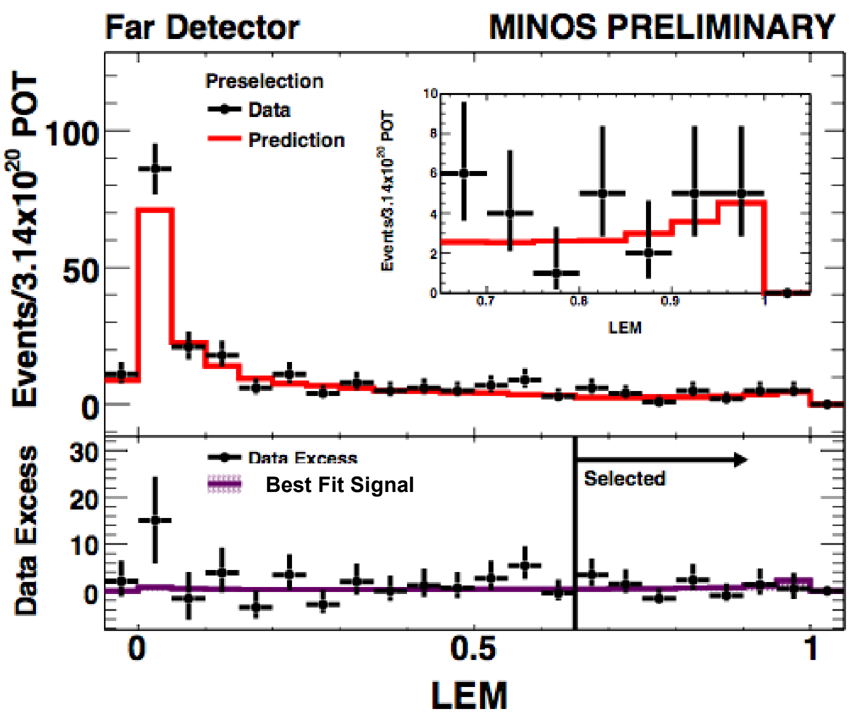


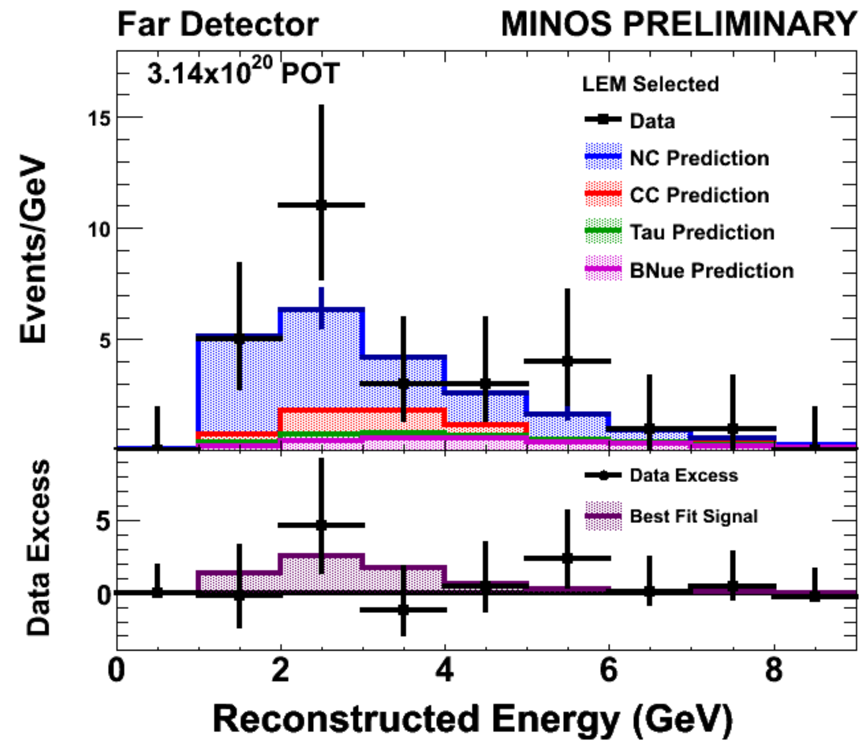
Observation: 35 events

Expected Background: 27 ± 5(stat) ± 2(syst) events

ν_e Selected Far Data

LEM (Secondary Selection Method)



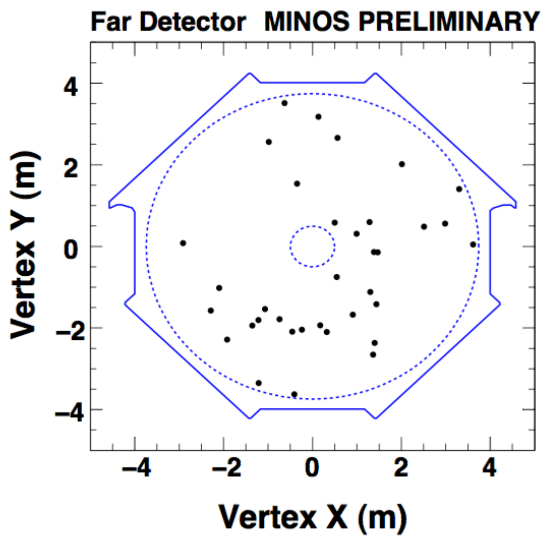


Observation: 28 events

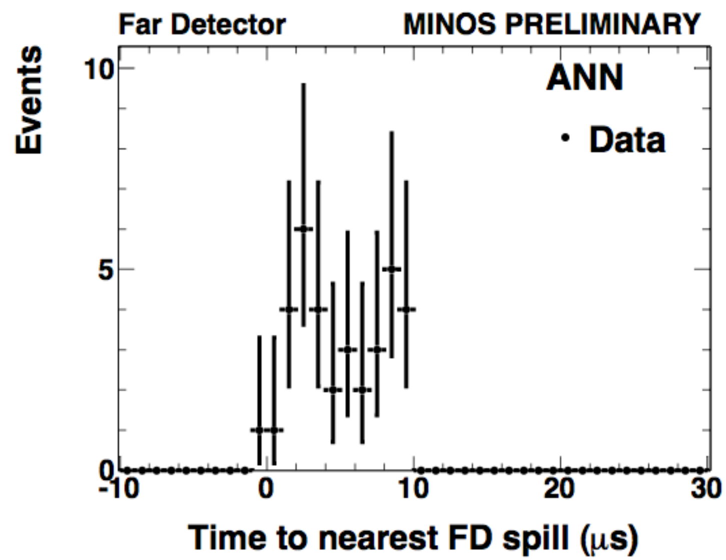
Expected Background: 22 ± 5(stat) ± 3(syst) events

Far Data Distributions

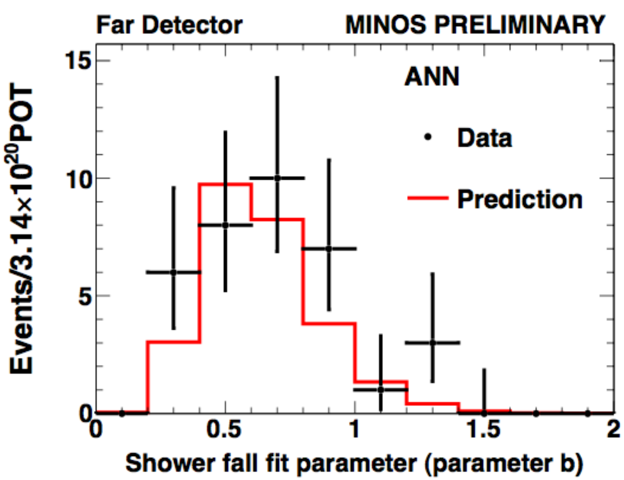
Vertex

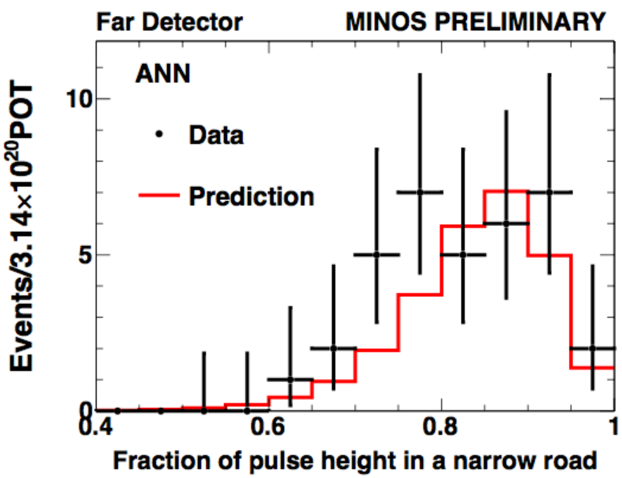


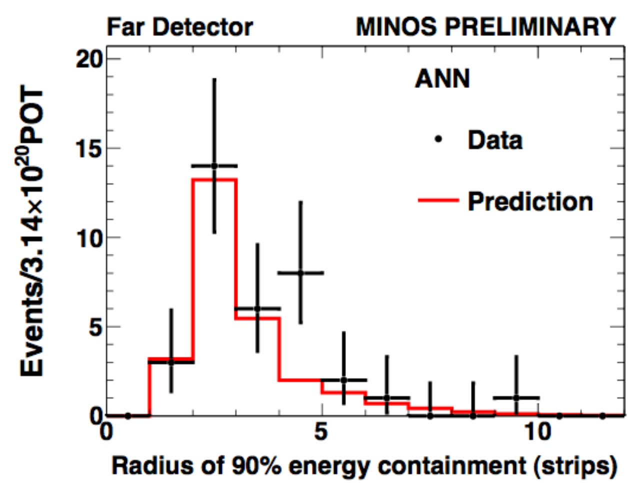
Timing



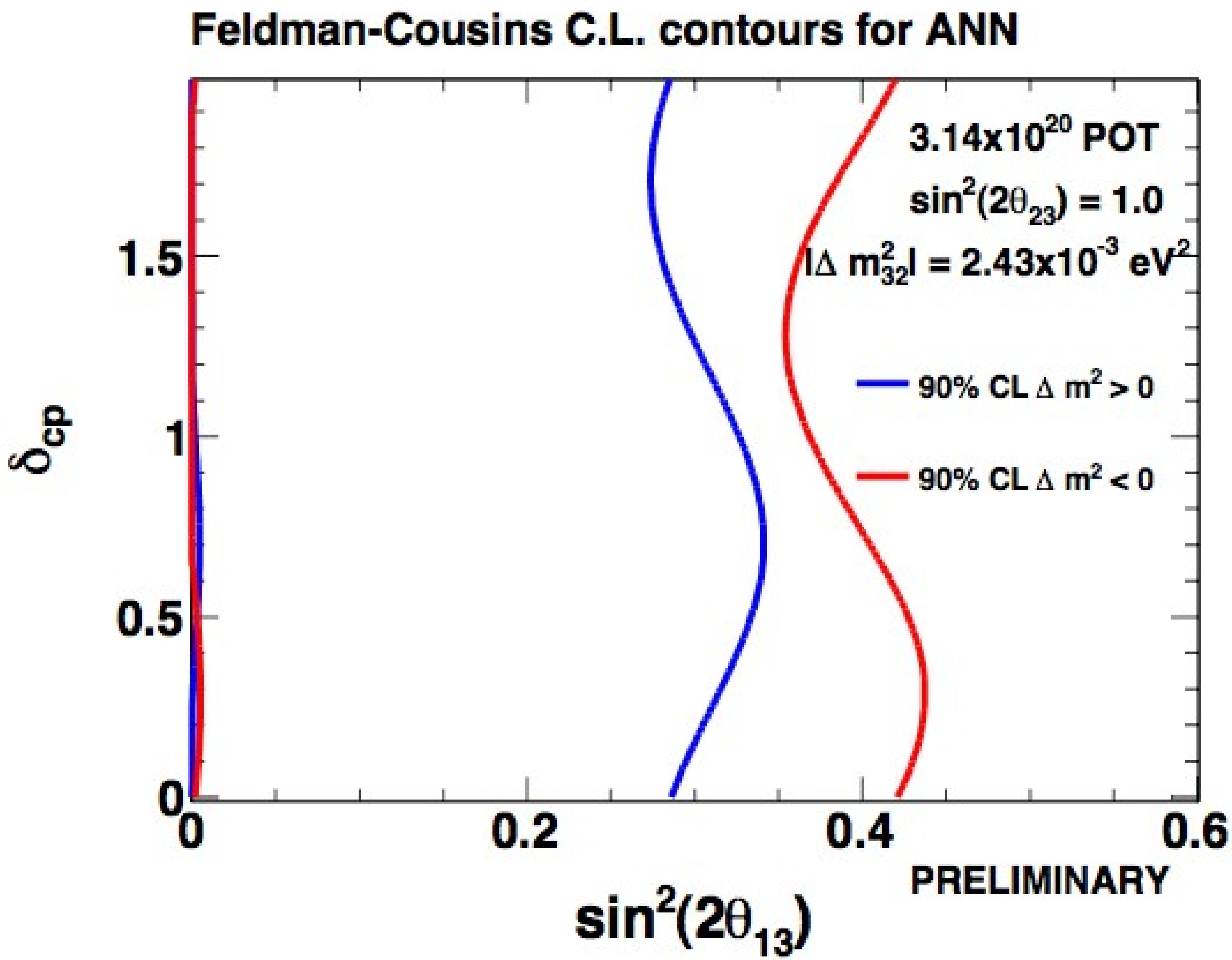
Some ANN variables



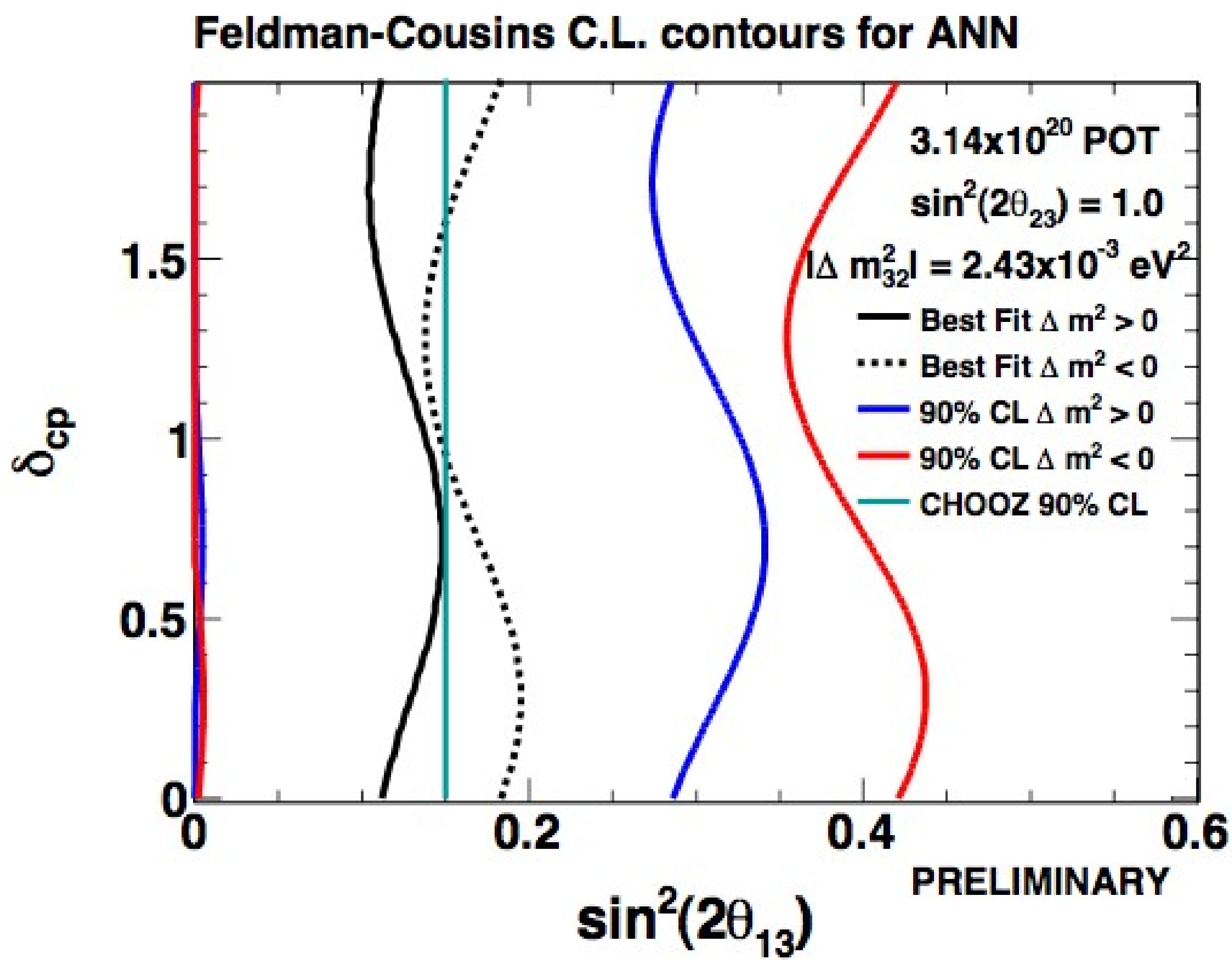




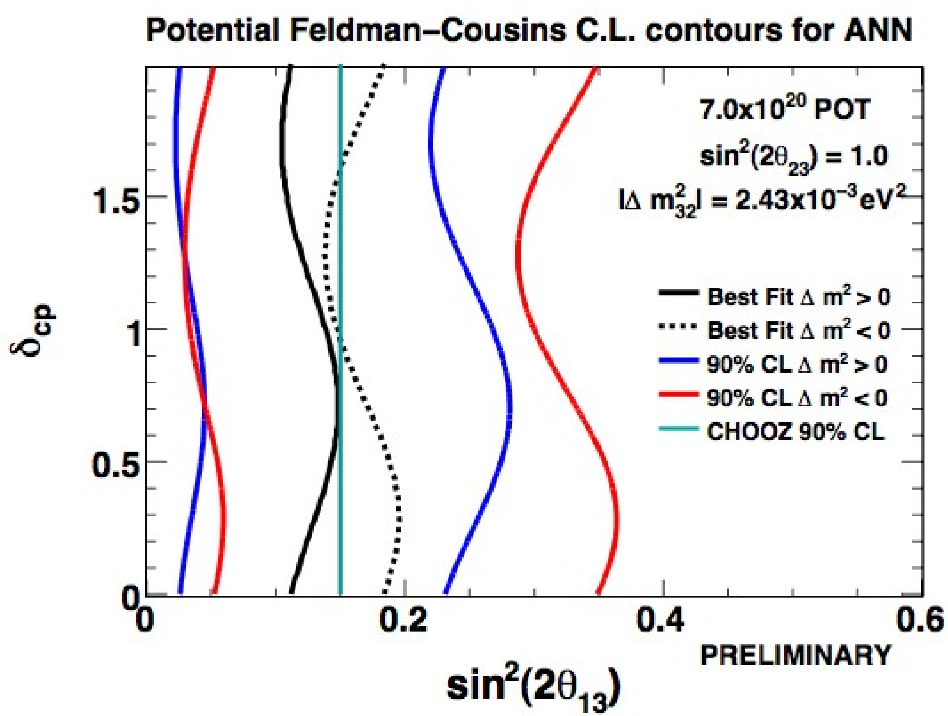
90% Confidence Level



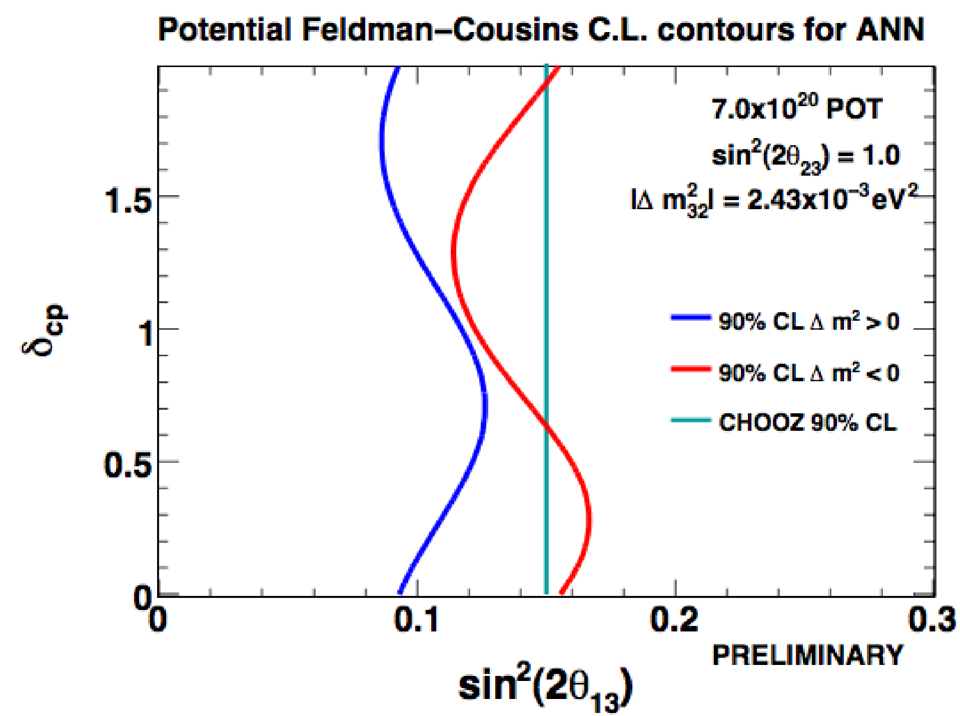
90% Confidence Level



Future Prospects: 7e20 POT



Future result if the data excess persists



Future result if data excess goes away with more statistics

Summary

- We have obtained our first results on the search for ν_e appearance in MINOS

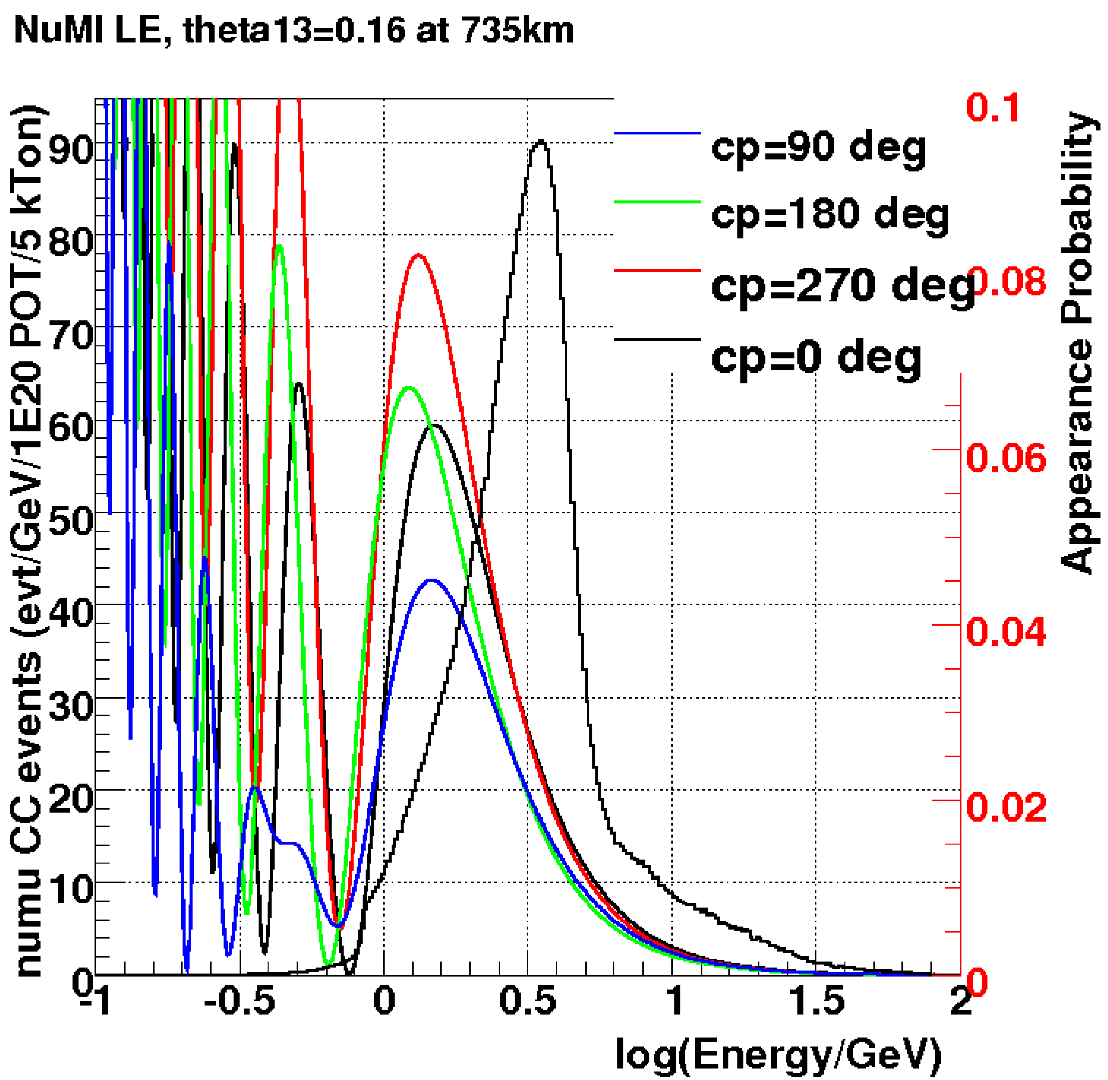
- We observed 35 events with a background expectation of 27 ± 5(stat) ± 2(syst) for 3.14e20 POT

- We set a 90% CL limit of $\sin^2 2\theta_{13} < 0.29$
  (normal mass hierarchy, $\delta=0$)

- We are close to doubling this data in the current running – next results with >7e20 POT!

Backup Slides

ν_e appearance at MINOS

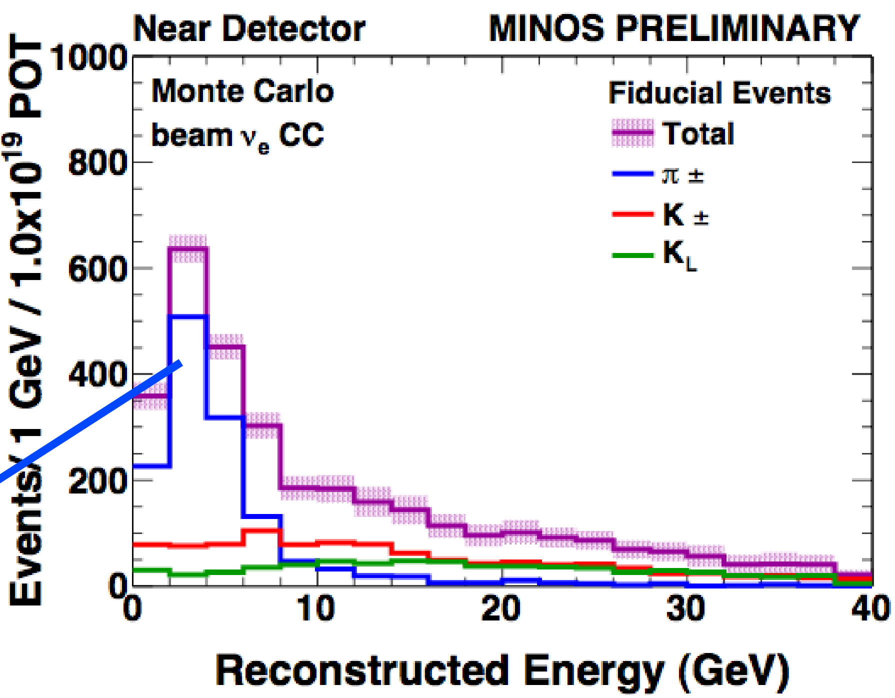


Beam ν_e component

Neutrino beam has 1.3% of ν_e contamination from pion and kaon decays.

Region of interest for the ν_e oscillation analysis, 1-8GeV, dominated by events from secondary muon decays:

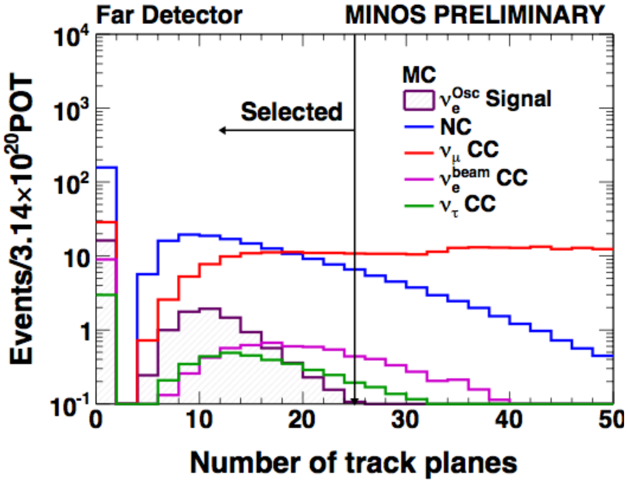
$$\begin{aligned} \pi^+ \quad \rightarrow \quad & \mu^+ \nu_\mu \\ & \hookrightarrow e^+ \bar{\nu}_\mu \nu_e \end{aligned}$$

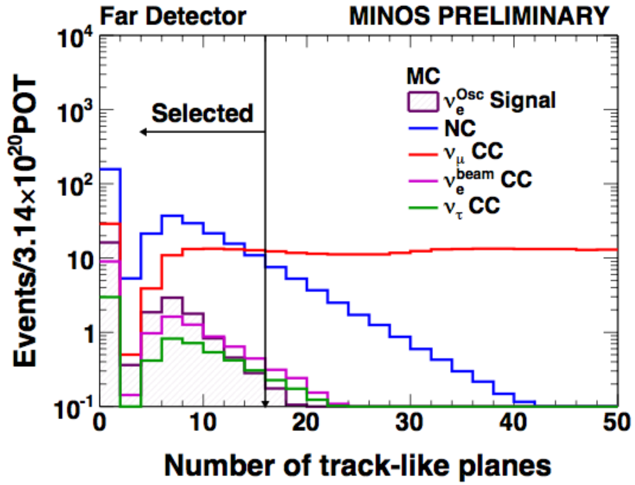


Near and Far beam ν_e spectra are constrained by using ν_μ events from several beam configurations.

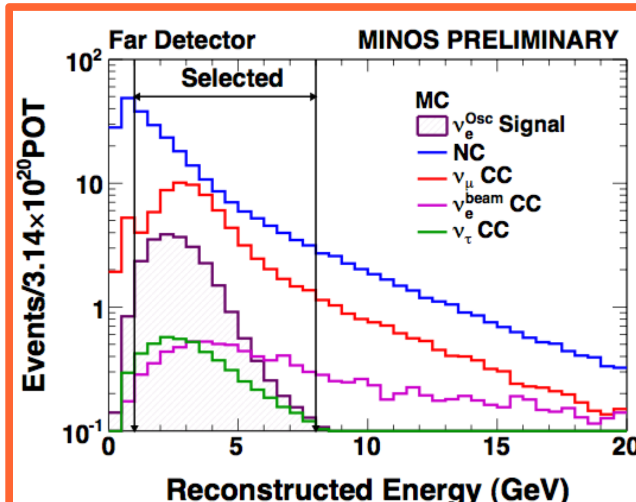
Uncertainties on the flux in the region of interest are ~10%

Preselection

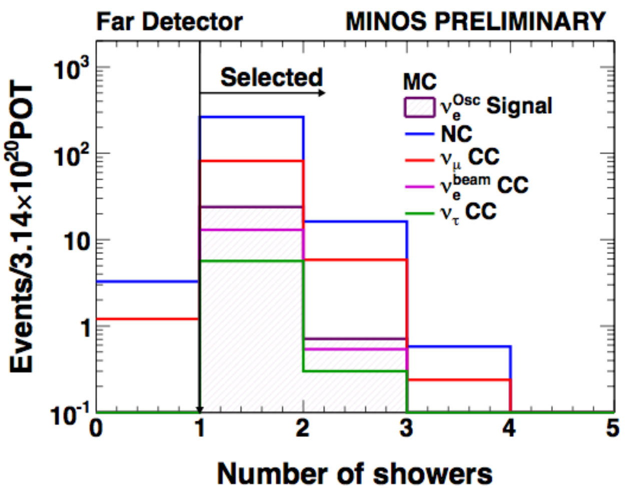


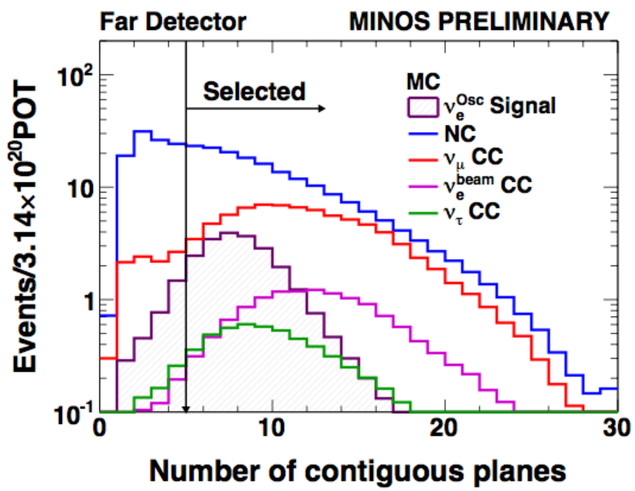


Track length



Reconstructed energy





At least one shower; 4 hit planes in a row

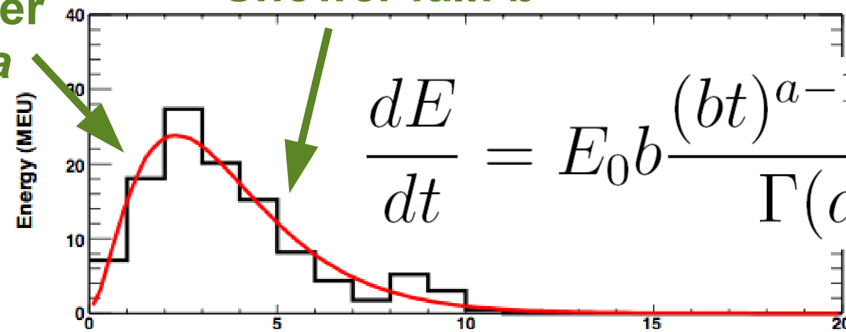
Data Reduction

	data	eff	MC	eff
fiducial	1188		1221.4	
trk	444	37.4%	445.6	36.5%
trklike	410	34.5%	410.3	33.6%
n shw	406	34.2%	406.4	33.3%
cont. pln	286	24.1%	298.5	24.4%
E >1 GeV	271	22.8%	282.8	23.2%
E < 8 GeV	227	19.11%	229.3	18.8%

ANN variables

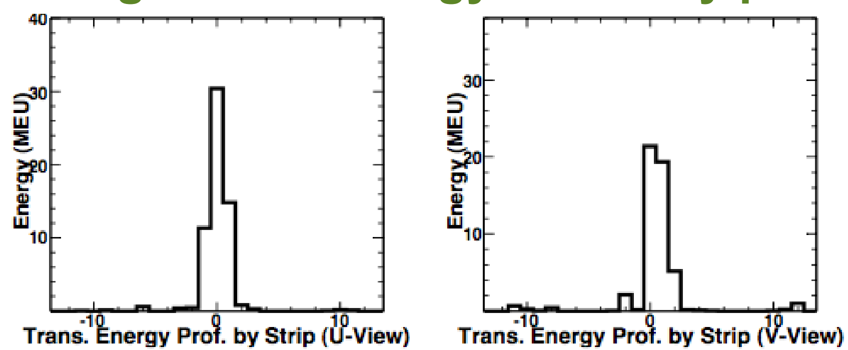
Shower fall: *b*

Shower rise: *a*



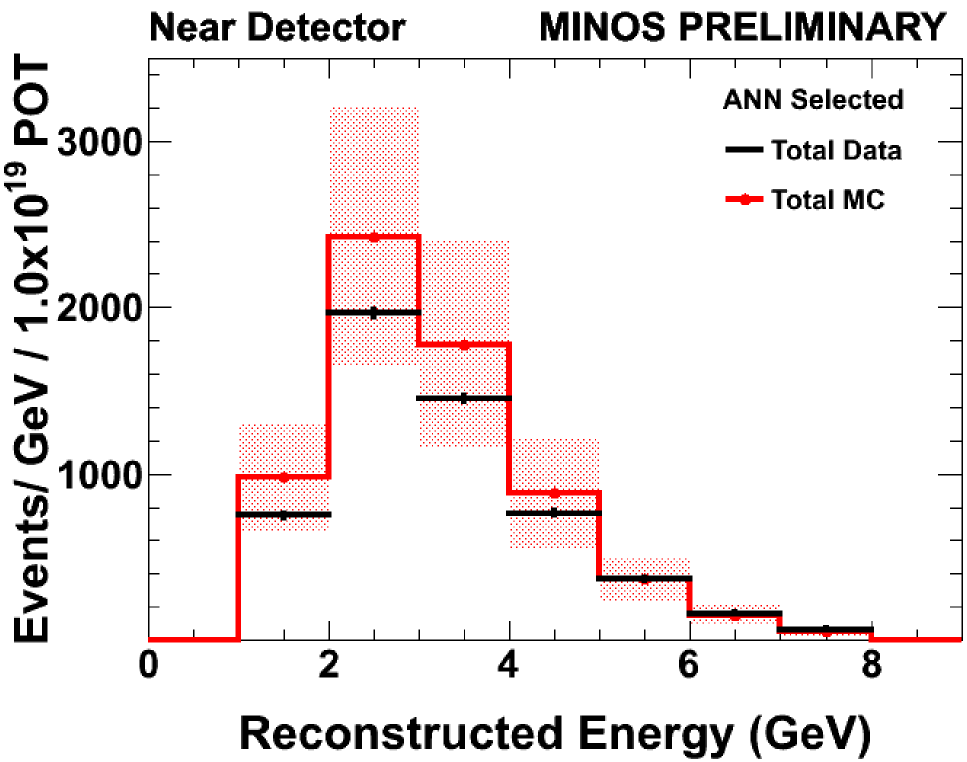
$$\frac{dE}{dt} = E_0 b \frac{(bt)^{a-1} e^{-bt}}{\Gamma(a)}$$

Longitudinal Energy Profile by plane



Transverse Energy Profile by strip

Near Detector ν_e candidates



The events that pass our selection cuts are from a kinematic region where hadronization is not well-modeled

→ Large uncertainties on the MC

→ Data/MC discrepancy not surprising

Each background component (CC ν_μ, NC, beam ν_e) must be extrapolated to the far detector separately.

We should not rely on MC for the relative size of CC ν_μ, NC, and beam ν_e components of the background.

→ we have two data-driven methods

Data-Driven Background Separation: Horn On/Horn Off

Number of selected data events in the horn off and horn on configurations can be related by the **horn off to horn on ratios** for each component.

Solve for N_{CC}^{ON} and N_{NC}^{ON}

data

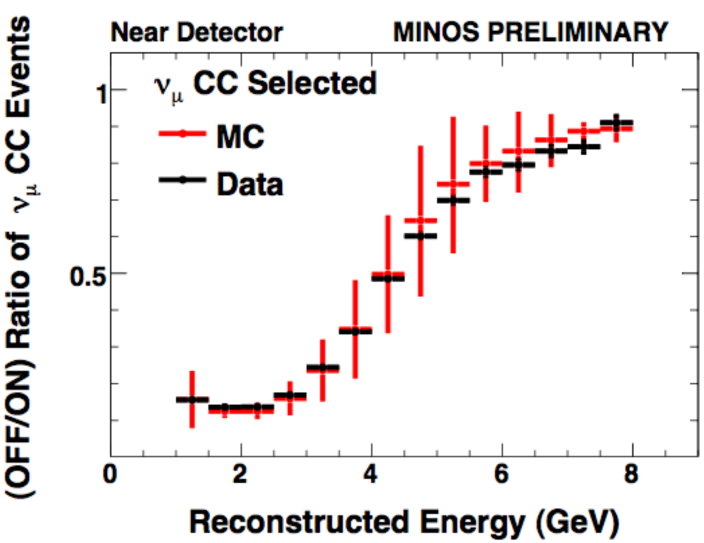
MC

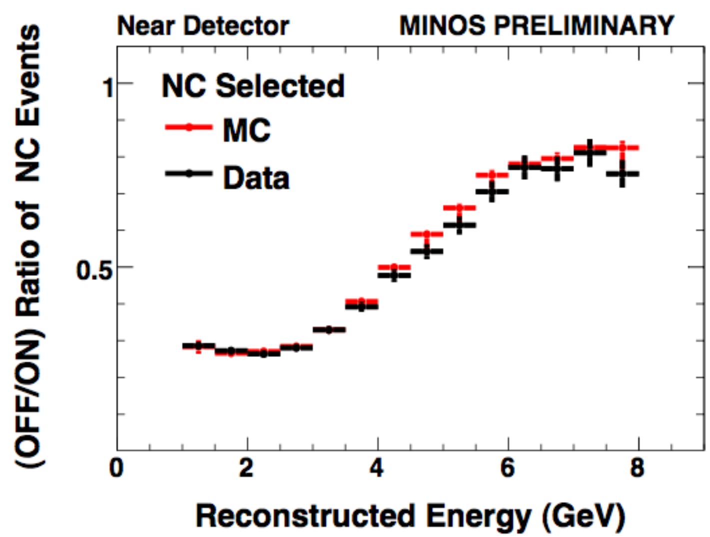
$$N^{ON} = N_{CC}^{ON} + N_{NC}^{ON} + N_{e}^{ON}$$

$$N^{OFF} = r_{CC} N_{CC}^{ON} + r_{NC} N_{NC}^{ON} + N_{e}^{OFF}$$

where $r_X = N_X^{OFF}/N_X^{ON}$

MC

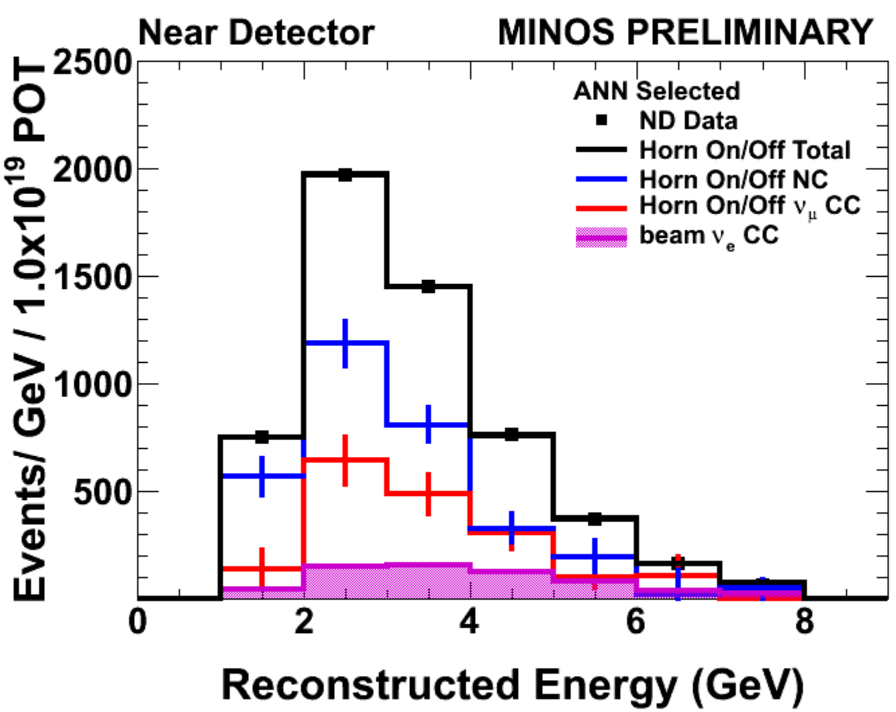




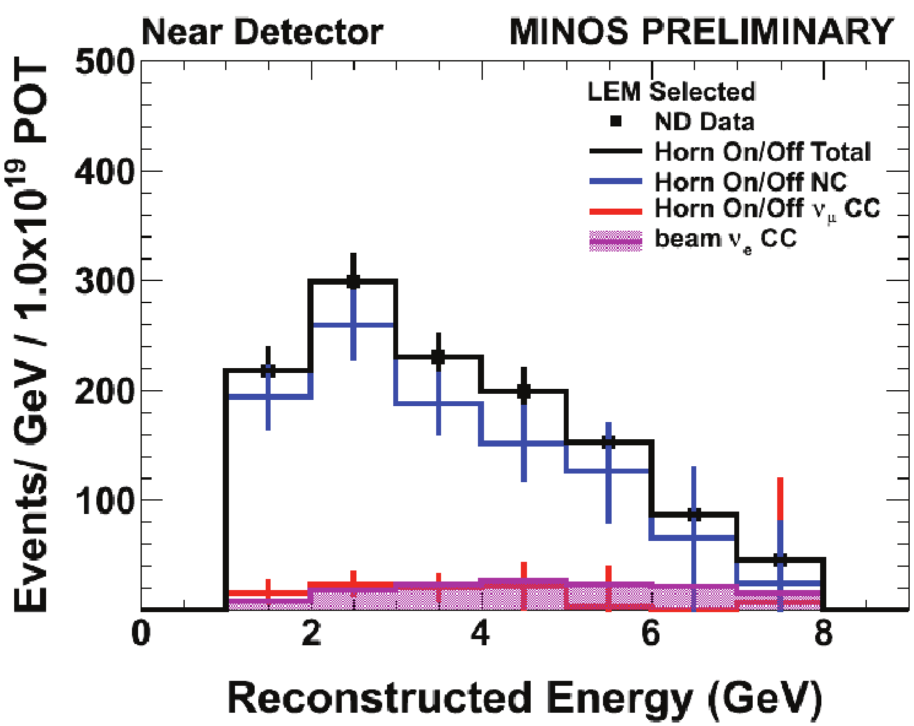
Select CC-like and NC-like events in the fiducial volume and compare data and MC horn off to horn on ratios – **MC models the ratios well.**

Data-Driven Background Separation: Horn On/Horn Off

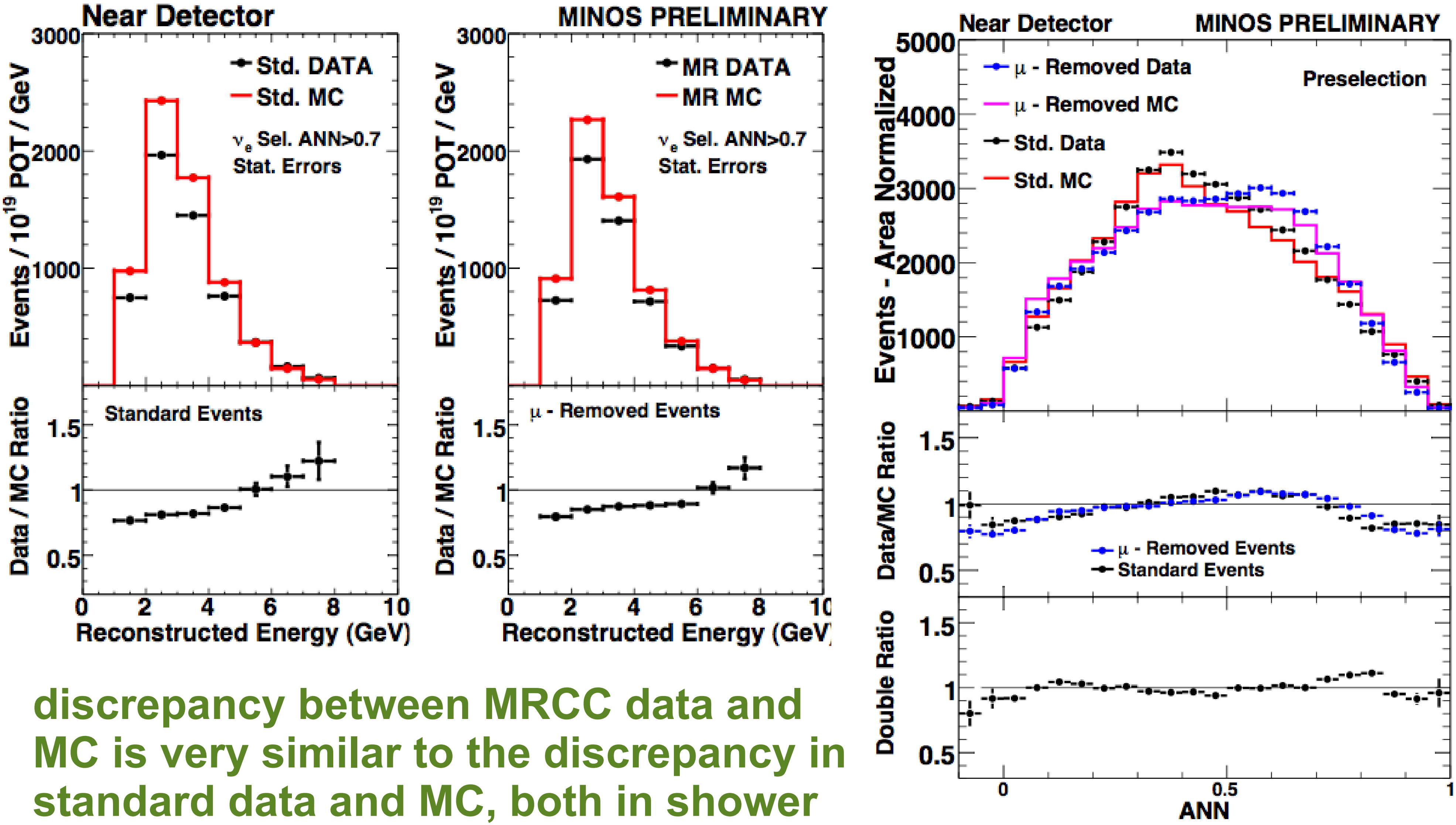
Horn On Data



Horn Off Data

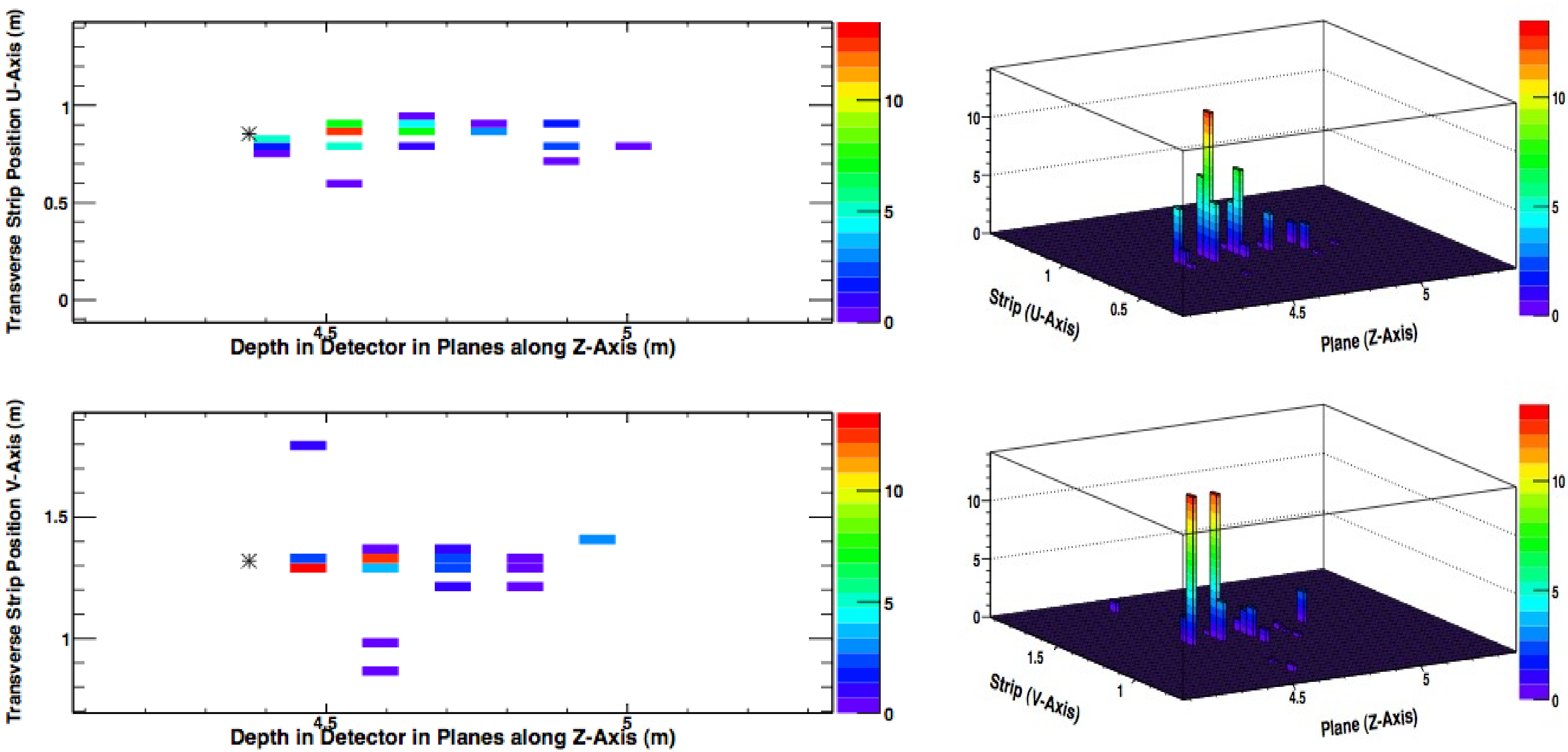


Data-Driven Background Separation: MRCC



discrepancy between MRCC data and MC is very similar to the discrepancy in standard data and MC, both in shower shape and energy

Far Detector ν_e Candidate Event Display



reconstructed energy: 4.6 GeV

MRE and Signal Efficiency

Muon Removed w/ Electron Added (MRE)

Take muon removed events, add an electron and re-reconstruct

Allows us to simulate signal events with a real hadronic shower

Apply ν_e selection to MRE data and MRE MC – ratio is used to correct signal efficiency